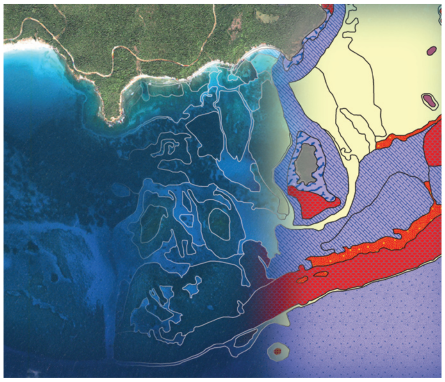
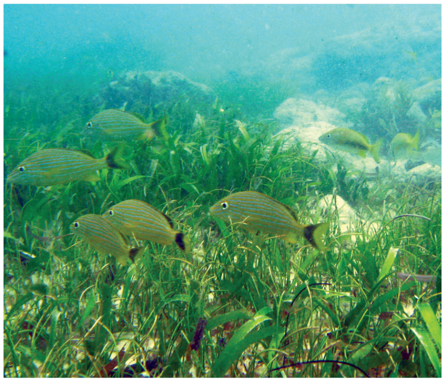
An Ecological Characterization of the Marine Resources of Vieques, Puerto Rico

Part II: Field Studies of Habitats, Nutrients, Contaminants, Fish, and Benthic Communities



May 2010

Prepared by NOAA's
National Centers for Coastal Ocean Science
Center for Coastal Monitoring and Assessment
and
Center for Coastal Fisheries and Habitat Research
In Partnership with
NOAA's Office of Response and Restoration

NOAA Technical Memorandum NOS NCCOS 110

ACKNOWLEDGEMENTS
The authors wish to thank Jason Rolfe, Diane Wehner, and David Holst with the Office of Response and Restoration for their assistance throughout the duration of this project. Thanks to Kimberly Edwards, Chris Taylor, Manoj Shivlani, and John Noles for providing helpful comments to improve this document. Funding was provided by NOAA's Office of Response and Restoration through an appropriation from Congress to support cleanup and restoration activities in Vieques. Additional support was provided by the National Centers for Coastal Ocean Science (NCCOS) and NOAA's Coral Reef Conservation Program (CRCP). Specific acknowledgements are provided following each chapter.

CITATIONS:

Citation for the entire document:
Bauer, L.J. and M.S. Kendall (eds.). 2010. An Ecological Characterization of the Marine Resources of Vieques, Puerto Rico Part II: Field Studies of Habitats, Nutrients, Contaminants, Fish, and Benthic Communities. NOAA Technical Memorandum NOS NCCOS 110. Silver Spring, MD. 174 pp.

Example citation for an individual chapter (example of Chapter 6):
Whitall, D.R., A.L. Mason, A.S. Pait, V Ransibrahmanakul and J.D. Christensen. 2010. Characterization of Spatial and Temporal Nutrient Dynamics. pp. 151-168. In: Bauer and Kendall (eds.), An Ecological Characterization of the Marine Resources of Vieques, Puerto Rico Part II: Field Studies of Habitats, Nutrients, Contaminants, Fish, and Benthic Communities. NOAA Technical Memorandum NOS NCCOS 110. Silver Spring, MD. 174 pp.

An Ecological Characterization of the Marine Resources of Vieques, Puerto Rico Part II: Field Studies of Habitats, Nutrients, Contaminants, Fish, and Benthic Communities

Biogeography Branch / Coastal and Oceanographic Assessment, Status and Trends (COAST) Branch
Center for Coastal Monitoring and Assessment (CCMA)
NOAA/NOS/National Centers for Coastal Ocean Science
1305 East-West Highway (SSMC-4, N/SCI 1)
Silver Spring, MD 20910

Center for Coastal Fisheries and Habitat Research (CCFHR)
NOAA/NOS/National Centers for Coastal Ocean Science
101 Pivers Island Road
Beaufort, NC 28516

NOAA Technical Memorandum NOS NCCOS 110

May 2010

Editors:
Laurie J. Bauer
Matthew S. Kendall

Authors:

Timothy A. Battista	Matthew S. Kendall	Varis Ransiibrahmanakul
Laurie J. Bauer	W. Judson Kenworthy	David R. Whitall
John S. Burke	Brooke Landry	Adam G. Zitello
John D. Christensen	Andrew L. Mason	
Brian Degan	Anthony S. Pait	
S. Ian Hartwell	Jenny Vander Pluym	

United States Department of Commerce	National Oceanic and Atmospheric Administration	National Ocean Service
Gary Locke Secretary	Jane Lubchenco Administrator	David Kennedy Acting Assistant Administrator

ABOUT THIS DOCUMENT

This report is Part II of an ecological characterization of the marine resources of Vieques, Puerto Rico. The purpose of this work, conducted by NOAA's National Centers for Coastal Ocean Science (NCCOS) in consultation with NOAA's Office of Response and Restoration and other local and regional partners, was to provide natural resource managers with a spatially comprehensive characterization of the marine ecosystem surrounding Vieques. In the first part of this assessment, previously existing data and descriptions from published reports and assessments were integrated into a synthesis report.

Part II of this assessment is a joint NCCOS effort encompassing the work of CCMA's Biogeography Branch, CCMA's Coastal and Oceanographic Assessment, Status and Trends (COAST) Branch, and the Center for Fisheries and Habitat Research (CCFHR). This work builds upon previous efforts by presenting new data on benthic habitats, associated biological communities, nutrients, and contaminant concentrations in coral and sediments. Together, both components of the characterization will provide research and monitoring tools in order to support effective management and conservation of the island's marine resources.

Funding for this project was provided by NOAA's Office of Response and Restoration, Coral Reef Conservation Program, and National Centers for Coastal Ocean Science. For more information on this work and other CCMA and CCFHR projects, please see:

http://ccma.nos.noaa.gov/,
http://www.ccfhr.noaa.gov/about/beaufort.html
and
http://ccma.nos.noaa.gov/ecosystems/coralreef/vieques.html

Direct questions or comments to:

Mark E. Monaco, Ph.D.
Acting Director, Center for Coastal Monitoring and Assessment
National Oceanic and Atmospheric Administration
1305 East West Highway
SSMC4, N/SCI-1
Silver Spring, MD 20910
Phone: (301) 713-3028 x160

EXECUTIVE SUMMARY

Since the 1940s, portions of the Island of Vieques, Puerto Rico have been used by the United States Navy (USN) as an ammunition support detachment and bombing and maneuver training range. In April 2001, the USN began phasing out military activities on the island and transferring military property to the U.S. Department of the Interior, the Municipality of Vieques, and the Puerto Rico Conservation Trust. A small number of studies have been commissioned by the USN in the past few decades to assess selected components of the coral reef ecosystem surrounding the island; however, these studies were generally of limited geographic scope and short duration. The National Oceanic and Atmospheric Administration's (NOAA) National Centers for Coastal Ocean Science (NCCOS), in consultation with NOAA's Office of Response and Restoration (OR&R) and other local and regional experts, conducted a more comprehensive characterization of coral reef ecosystems, contaminants, and nutrient distribution patterns around Vieques. This work was conducted using many of the same protocols as ongoing monitoring work underway elsewhere in the U.S. Caribbean and has enabled comparisons among coral reef ecosystems in Vieques and other locations in the region.

This characterization of Vieques' marine ecosystems consists of a two part series. First, available information on reefs, fish, birds, seagrasses, turtles, mangroves, climate, geology, currents, and human uses from previous studies was gathered and integrated into a single document comprising Part I of this two part series (Bauer et al. 2008). For Part II of the series, presented in this document, new field studies were conducted to fill data gaps identified in previous studies, to provide an island-wide characterization, and to establish baseline values for the distribution of habitats, nutrients, contaminants, fish, and benthic communities. An important objective underlying this suite of studies was to quantify any differences in the marine areas adjacent to the former and current land-use zoning around Vieques. Specifically of interest was the possibility that either Naval (e.g., practice bombing, munitions storage) or civilian activities (e.g., sewage pollutants, overfishing) could have a negative impact on adjacent marine resources. Measuring conditions at this time and so recently after the land transfer was essential because present conditions are likely to be reflective of past land-use practices. In addition, the assessment will establish benchmark conditions that can be influenced by the potentially dramatic future changes in land-use practices as Vieques considers its development.

This report is organized into seven chapters that represent a suite of interrelated studies. Chapter 1 provides a short introduction to the island setting, the former and current land-use zoning, and how the land zoning was used to spatially stratify much of the sampling. Chapter 2 is focused on benthic mapping and provides the methods, accuracy assessment, and results of newly created benthic maps for Vieques. Chapter 3 presents the results of new surveys of fish, marine debris, and reef communities on hardbottom habitats around the island. Chapter 4 presents results of flora and fauna surveys in selected bays and lagoons. Chapter 5 examines the distribution of nutrients in lagoons, inshore, and offshore waters around the island. Chapter 6 is focused on the distribution of chemical contaminants in sediments and corals. Chapter 7 is a brief summary discussion that highlights key findings of the entire suite of studies.

The main findings of each Chapter are as follows:

Chapter 1: Introduction

- From west to east, the former land-use zones used to stratify adjacent marine areas and guide sampling for many components of these studies were: 1) Naval Ammunition Support Detachment, 2) Civilian Area, 3) Eastern Maneuver Area/Secondary Impact Area, 4) Live Impact Area, and 5) Punta Este Conservation Area.
- The 3 generalized objectives shared by the studies were: 1) quantify differences in marine environments offshore from the various land-use zones, 2) compare environmental values in Vieques to those available elsewhere in Puerto Rico and the US Virgin Islands, and 3) establish baseline values to compare with future studies as land-use practices and resource conditions change around Vieques.

Chapter 2: Benthic Habitat Maps

- The objective was to create updated and improved benthic habitat maps of Vieques. Relative to the latest comprehensive maps available, a smaller mapping unit (1000 versus 4000 m^2), more recent satellite and aerial imagery (2006-2008 versus 1999), and more detailed classification scheme were used.
- Benthic features were classified according to five attributes: 1) geographic zone, 2) habitat structure, 3) dominant cover, 4) live coral cover, and 5) percent hardbottom.
- 350 km^2 of seafloor features around Vieques were mapped. Unconsolidated Sediments and Hardbottom accounted for 66.6% and 33.4% of the mapped area, respectively. Algae was the dominant cover on hardbottom and seagrass dominated softbottom.
- Percent live coral cover was <10% for 93% of the mapped area, while the remainder was mapped as 10% -<50%.

- Classification accuracy was 89% correct for detailed habitat structures.

Chapter 3: Reef/hardbottom habitats, fish and marine debris

- Objectives were to characterize benthic and fish communities on hardbottom around Vieques, identify differences in communities adjacent to former land use zones, and to establish baseline values for change detection.
- A stratified random design was used to select 75 sites for benthic and fish community surveys around Vieques. Former land-use zones and north/south coasts of Vieques were used as strata.
- Turf algae accounted for the highest overall mean percent cover, followed by macroalgae, gorgonians, crustose/calcareous algae, hard coral, and sponges. Hard coral cover was generally low, with an overall mean of 3.4 (±0.5)%. Sites with the highest coral cover were generally located on reefs southwest of the island.
- The fish community observed in the study consisted of 34 taxonomic families and 110 species. While individuals from the families Labridae (wrasses) and Pomacentridae (damselfishes) were the most numerically abundant, surgeonfishes (Family Acanthuridae) and parrotfishes (Family Scaridae) accounted for the highest proportion of biomass.
- Several fish metrics varied on a north-south and/or east-west gradient, although there was a high degree of variability among strata. Differences in fish communities on the north vs. south side of the island were attributed partly to predominant habitat structure.
- Vieques is similar in terms of benthic cover, total fish abundance and biomass to other nearby locations in Southwest Puerto Rico, St. Croix, and St. John in the USVI.
- Differences in fish and benthic communities among strata could not be conclusively linked to former land use patterns.

Chapter 4: Marine flora and fauna of four lagoons

- Objectives were to characterize the flora and fauna of four lagoons (Puerto Mosquito, Puerto Ferro Ensenada Honda, and Puerto Negro), compare these communities to those of the insular shelf, and identify critical ecosystem services provided by these habitats.
- A stratified random design across depths and habitat types was used to position diverse sampling activities including quadrats, sediment cores, visual fish surveys, and push nets.
- Differences in flora and fauna of lagoons appear driven partly by turbidity and openness or degree of water exchange with adjacent shelf habitats. Turbid bays like Puerto Mosquito and Puerto Ferro are contrasted with more open lagoons like Ensenada Honda and Puerto Negro.
- Seagrass cover was higher in vegetation beds of the open lagoons and the shelf compared to lagoons with restricted circulation. In contrast seagrass species richness was higher in lagoons with restricted circulation than in open lagoons or the shelf.
- Soft-bottom faunal communities of both lagoons and the shelf were dominated by juveniles however the lagoon community was more diverse and included commercially and ecologically important species absent as juveniles from the shelf.
- The high floral and faunal diversity of lagoons and evidence of their role as nursery areas indicates that lagoons are a critical component of the Vieques coastal ecosystem.

Chapter 5: Contaminants

- Objectives were to characterize chemical contamination in the nearshore waters and lagoon areas of Vieques, identify differences in contamination based on former land-use, establish baseline values for change detection, and identify sites where sediment contamination exceeds established guidelines.
- A stratified random design was used to select 78 sites for sediment and 35 sites for coral tissue sampling around Vieques. Former land-use zones, lagoon versus offshore, and north/south coasts of Vieques were used as strata.
- 150 chemical contaminants including metals, pesticides, and energetic compounds (explosives) were analyzed.
- Overall, contaminant concentrations were below established sediment quality guidelines, sediments from lagoons typically had higher concentrations than offshore sites, and sediments had higher concentrations of trace and major elements (mostly metals) than corals.
- DDT (at four sites) and chromium (at one site) were detected in sediment samples above established sediment quality guidelines. At one site near Blue Beach, the concentration of DDT was over an order of magnitude higher than the established NOAA sediment quality guideline.
- Sediment concentrations of polycyclic aromatic hydrocarbons were significantly higher in the strata that included the former Naval Ammunition Support Detachment. The concentration of cadmium was significantly higher in the former Live Impact Area. No sites, however, had concentrations that were likely to affect sediment-dwelling biota.
- Sediment samples analyzed for 14 energetics yielded no confirmed detections.

Chapter 6: Nutrients

- Objectives were to identify localized hot spots of nutrient levels, north/south or east/west gradients in nutrient concentration, and to establish baseline values for change detection.

- A stratified random design was used to select 40 sampling stations with lagoon, inshore, and offshore waters as spatial strata. Sampling was repeated at each station approximately monthly from July 2007 to March 2008.
- Water samples were analyzed for nitrate, nitrite, silicate, orthophosphate, ammonium, urea, total nitrogen, and total phosphorus.
- There was no evidence of anthropogenic over-enrichment of nutrients.
- Nutrient concentrations were generally low and similar in magnitude to those measured elsewhere in Puerto Rico at La Parguera and Jobos Bay.
- Nitrogen and phosphorus concentrations were below published threshold values considered threatening for macroalgal overgrowth on coral reef ecosystems.
- The highest concentrations of nutrients were found in mangrove lined lagoons. It is hypothesized that this is a natural condition rather than nutrient pollution because the lagoons are shallow, poorly flushed, and naturally high in organic matter.

Chapter 7: Conclusions

- Overall, there was little evidence of any difference in marine resources, nutrients, or contaminants around Vieques offshore of the various former land-use zones.
- Chemical contaminant and nutrient levels, with a few localized exceptions, were generally below known levels of concern.
- There was no evidence of a statistical relationship between any of the spatial patterns in fish distribution, nutrient, or contaminant levels.
- Nutrient and contaminant values established in this study will serve as a baseline to evaluate the potential future development pressure on the island may have on the increased flux of these materials to coastal waters, thereby increasing stressors to coral reefs.
- It has been hypothesized that naval activities negatively impacted marine environments around Vieques. Conversely, the lack of residential and commercial development on two-thirds of the island formerly owned by the USN may have been a positive influence by preventing anthropogenic activities that are well documented elsewhere to harm marine environments. Although there were some differences found in biota among sampling strata and some elevated levels of contaminants and nutrients around the island, the results of this study do not support either of these hypotheses as a major factor structuring the marine environment of Vieques.
- Biota, nutrients, and contaminant levels around Vieques generally match those for other coral reef ecosystems in the Puerto Rico and US Virgin Islands region and appear to be shaped primarily by regional-scale processes rather than local factors.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1: INTRODUCTION

The following report is the second of a two-part series that provides an ecological characterization of the marine resources of Vieques, Puerto Rico. The overall objective was to provide natural resource managers with a spatially comprehensive characterization of the marine ecosystem surrounding Vieques. In the first part of this assessment, previously existing ecological data and descriptions from published reports and assessments were integrated into a synthesis report (Bauer et al. 2008). The Part I report is divided into chapters based on the physical environment (e.g., climate, geology, bathymetry), habitat types (e.g., reefs and hardbottom, seagrasses, mangroves) and major faunal groups (e.g., fish, turtles, birds). In Part II, newly collected data on fish, benthic habitats, contaminant concentrations in sediments and coral, and nutrients in coastal waters were analyzed in the context of historical land-use patterns in Vieques and then compared to other nearby regions in the U.S. Caribbean.

Image 1.1. View of Cayo Conejo and Roca Alcatraz. Photo: CCMA COAST Branch.

Vieques is an island municipality of the Commonwealth of Puerto Rico that is located approximately 11 km southeast of the main island of Puerto Rico in the Caribbean Sea (Figure 1.1). The island is approximately 33 km long and 7 km wide with a land area of about 127.4 km^2. The island and surrounding waters are characterized by a diversity of terrestrial, estuarine, and marine habitats, including two of Puerto Rico's three bioluminescent bays. The municipality includes two principal towns located on opposite sides of the mid-section of the island, Isabel Segunda on the north shore and Esperanza on the south coast. The 2000 Census estimated the population of Vieques at 9,106 (DOI 2007).

Patterns of human habitation and development are important factors when considering the present distribution and condition of the marine resources in Vieques. The island's landscape has undergone various stages of human development dating from the first record of occupation (ca. 200 BC, Langhorne 1987). Until the 1800s, Vieques was inhabited by native tribes and later by small Spanish, English, Dutch, and French settlements (Langhorne 1987). As Spain exerted greater control and developed colonization of the island in the early to mid-1800s, much of the land was cleared for sugar cane and timber harvesting, which removed the majority of native forests. Along with the rest of Puerto Rico, Vieques was ceded to the United States in 1898 following the Spanish-American War. The sugar industry flourished into the early 20th century, but waned into the 1920s and 30s. At the time of acquisition by the U.S. Navy, sugar was no longer a viable industry (Langhorne 1987).

Between 1941 and 1947, the United States annexed approximately two-thirds of the land on Vieques for use by the Navy as a base and training facility (Figure 1.2). The Naval Ammunition Support Detachment (NASD), located on the west end of the island, was used primarily for storage of ammunition. The municipality of Vieques (Civilian Area; CA), including the towns of Isabel Segunda and Esperanza, lay between the NASD and eastern Navy zones. The eastern half of the island consisted of the former Vieques Naval Training Range (VNTR) which, from west to east, was comprised of the Eastern Maneuver Area (EMA), Secondary Impact Area (SIA), Live Impact Area (LIA), and Eastern Conservation Area (ECA). Training activities conducted within the EMA, SIA, and LIA included air, sea, and maneuver warfare, air-to-ground (ATG) bombing, amphibious landings, and artillery training operations, among others. ATG activities were primarily localized within the LIA and adjacent waters. Locations of amphibious assault training activities included Green Beach, Yellow Beach, Blue Beach, Red Beach, and Purple Beach. Detailed information about prior Naval activities in Vieques can be found in a number of sources (DON 1979; DON 1986; DON 2001; GMI 2003; CH2M HILL 2004; GMI 2005).

Changes in land ownership began in 2001 and Naval training activities ceased in 2003. The 2009 distribution of land ownership is shown in Figure 1.3. In 2001, 17 km^2 of former Navy lands on western Vieques were transferred to the municipality, 3.2 km^2 to the Puerto Rico Conservation Trust (http://www.fideicomiso.org), and 12.5 km^2 to the Department of the Interior (DOI 2007). The Navy retained a small parcel of land for its Relocatable Over the Horizon Radar (ROTHR) facility. In 2003, the eastern Navy lands were also transferred to the Department of the Interior. The lands under jurisdiction of the DOI's Fish and Wildlife Service make up the Vieques National Wildlife Refuge (Figure 1.3; DOI 2007). In 2005, the former Navy areas of Vieques were added to

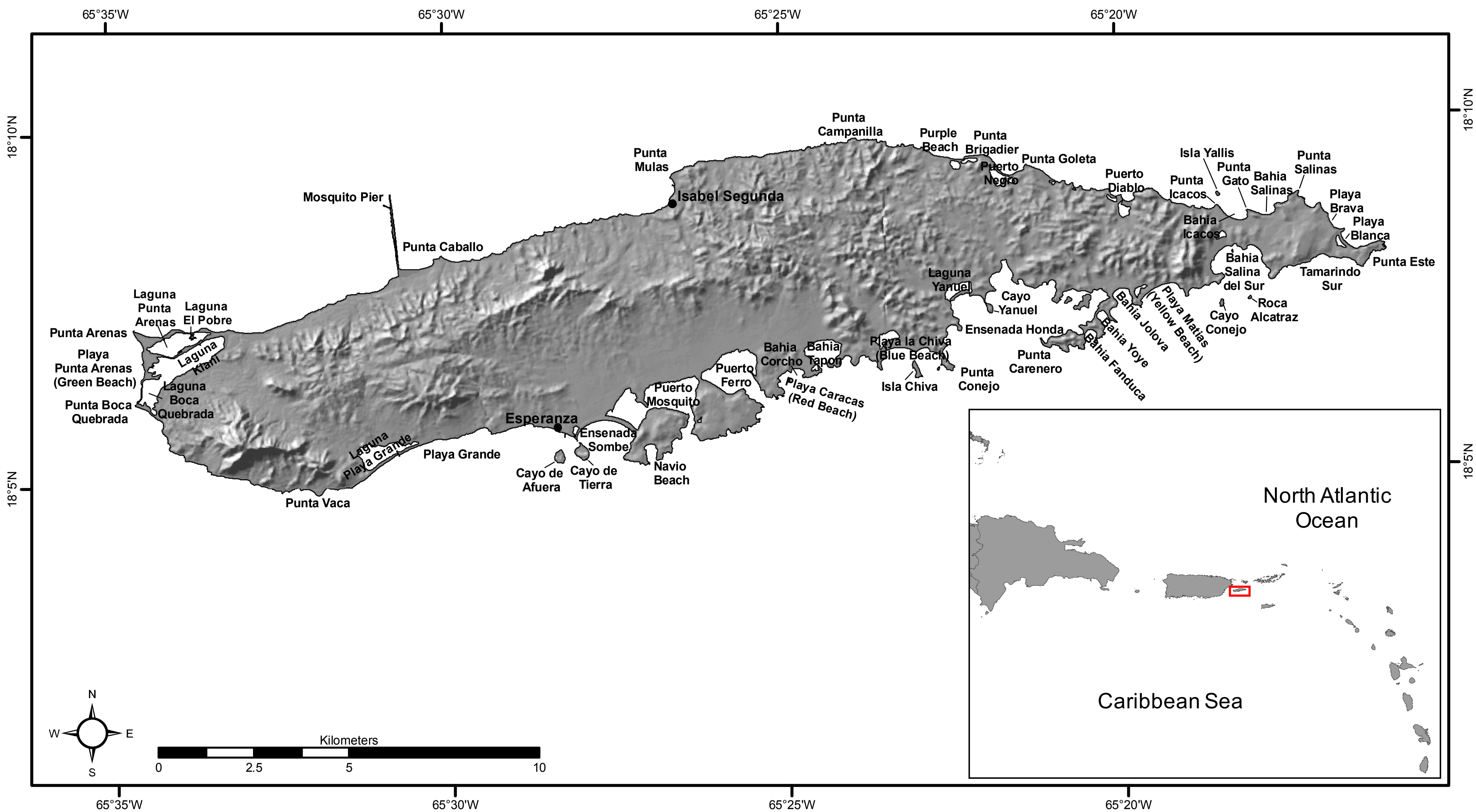


Figure 1.1. Location of Vieques, Puerto Rico.

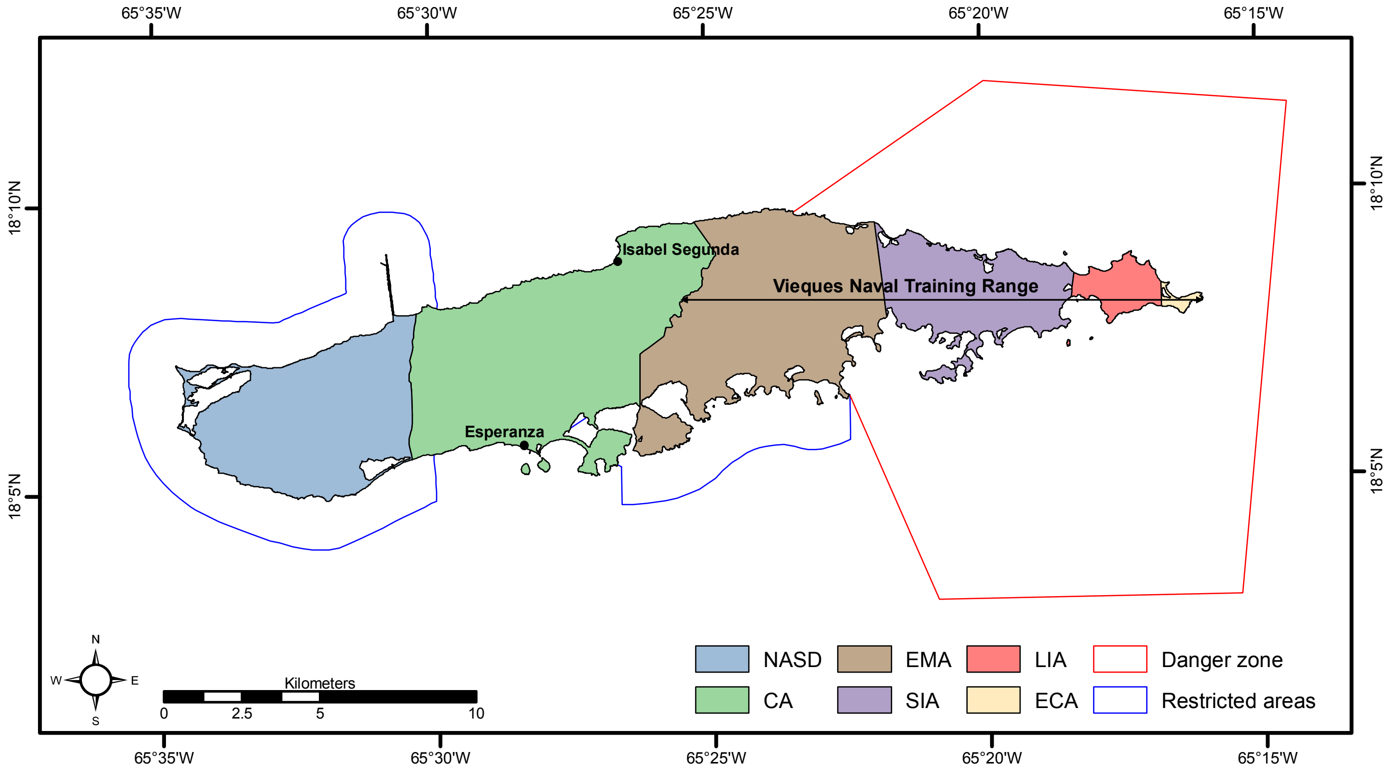


Figure 1.2. Former land ownership in Vieques from 1941 to land transfer in 2001 and 2003. Boundaries were provided by Geo-Marine, Inc. NASD= Naval Ammunition Support Detachment, CA=Civilian Area, EMA= the Eastern Maneuver Area, SIA= Secondary Impact Area, LIA= Live Impact Area, ECA= Eastern Conservation Area.

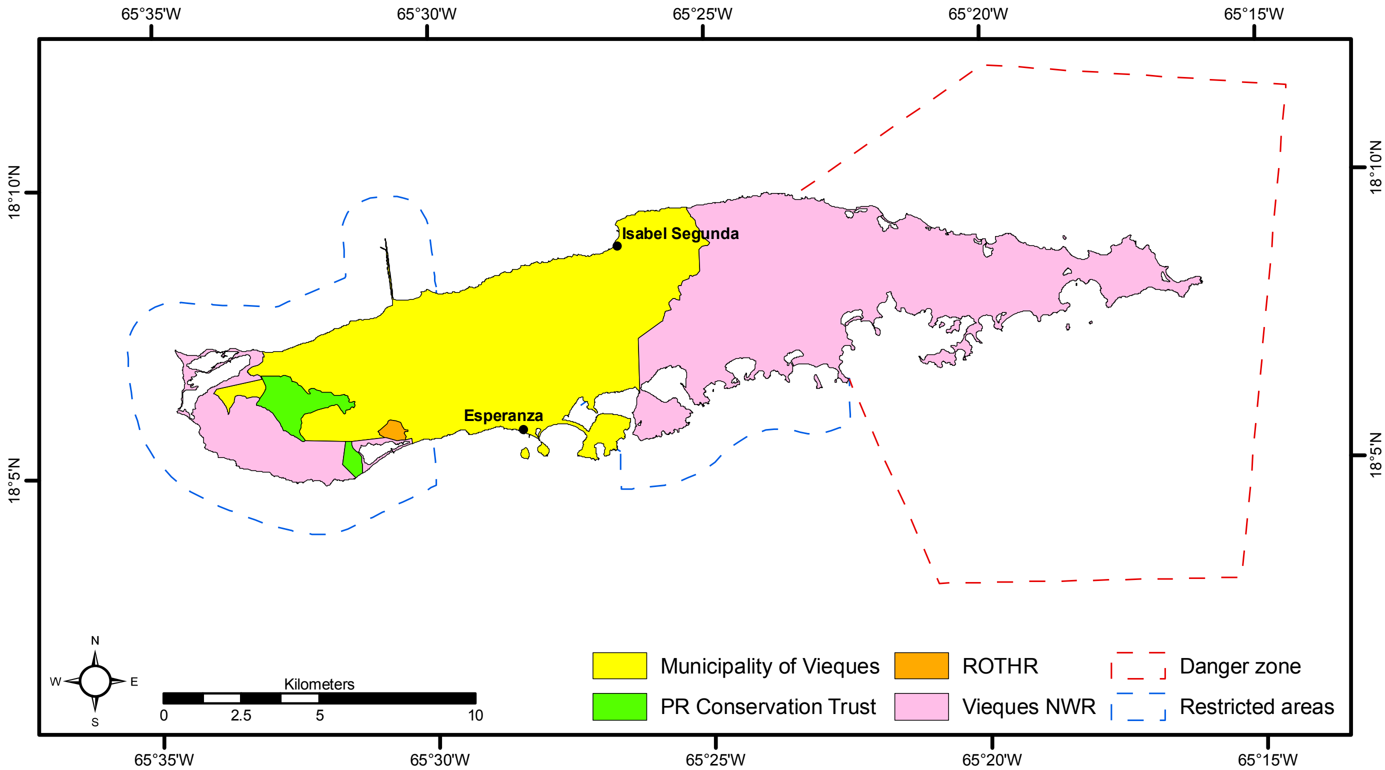


Figure 1.3. Land ownership distribution in Vieques as of 2008. Boundaries were provided by William Hernandez (US Fish and Wildlife Service). ROTHR = Relocatable Over the Horizon Radar; NWR = National Wildlife Refuge.

the National Priorities List (NPL or "Superfund"), legislation which requires the Navy to undertake activities to investigate and clean-up any contaminated areas identified by the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) (Federal Register 7182-7189 2005). Through this program, the Navy is currently removing all terrestrial unexploded ordnance (UXO), which often necessitates open detonation or "blow-in-place" of unexploded ordnance. Public access is currently restricted in a large part of the eastern refuge lands due to these activities and other remnant hazards.

Image 1.2. Puerto Ferro. Photo: CCMA COAST Branch.

Prior marine zoning included two restricted areas, on the west and south sides of the island, and a "danger zone" which encompassed the east end of the island and included the waters adjacent to the LIA (Figure 1.2). These areas were zoned with various levels of restricted access due to their uses and proximity to Navy activities (Code of Federal Regulations 2001a; Code of Regulations 2001b). The Danger Zone was open to navigation at all times except when firing and bombing practices were being conducted (Code of Federal Regulations 2001a). In the two restricted areas, access was prohibited at all times except for authorized personnel (Code of Federal Regulations 2001b).

A comprehensive assessment of the distribution and status of the marine resources of Vieques is timely in light of the recent land transfer, increases in development and tourism, and potential changes in marine zoning around the island. In Part I of this series, known data was compiled and integrated, and data gaps were identified. Specifically, it was recognized that while numerous reports have been published on the marine resources of Vieques, few have been island-wide assessments. Historically, surveys of fish and benthic habitats have focused on either military areas (e.g., GMI 2003) or non-restricted locations offshore of the municipality (e.g., Garcia-Sais et al. 2001). Similarly, assessments of chemical contaminants have typically been conducted in areas formerly owned by the U.S. Navy (see Chapter 5). Fewer reports have focused on the biological oceanography of the coastal waters. To our knowledge, no island-wide studies have been conducted on nutrient levels or primary productivity in lagoons or coastal waters of Vieques. Spatially comprehensive assessments of these factors would establish a baseline with which to monitor future changes, enable the comparison of areas adjacent to land regions that varied in use, and allow the island to be evaluated in context with neighboring islands in the U.S. Caribbean.

The impact of military activities on coral reef ecosystems has long been a subject of debate and was of interest to local resource managers, scientists, and stakeholders that were consulted when this characterization was begun. Two conflicting hypotheses exist. One theory is that there is lower habitat quality, degraded biological communities, and higher degree of contamination in sediments and biota offshore of former Navy areas in comparison to areas that did not experience such activity. Particular attention has been paid to the LIA due to the bombing exercises that took place there. Several reports have documented damage to reefs in the LIA that had been hit by ordnance (Rogers et al. 1978), particularly those located near bombing targets (DON 1980; Macintyre et al. 1983; DON 1986), and elevated contaminant levels in organisms adjacent to ordnance (Barton and Porter 2004). However, whether these local effects persist at a broader scale (e.g., island-wide level) has not sufficiently been investigated.

In contrast, because most of the Naval lands lacked residential and commercial development, one might expect there to be reduced runoff from anthropogenic activities that are known to harm marine resources and hence more intact ecosystems. In addition, since prior marine zoning restricted access to much of the coastal waters adjacent to the Navy lands (Figure 1.2), it is likely that fishing pressure would have been lower in these areas when these boundaries were enforced, providing a de facto marine protected area (MPA). To investigate these issues, sampling locations for two sections in this assessment (Chapters 3 and 5) were stratified by their adjacency to former land use. This enabled comparison of fish, benthic communities, and contaminant concentrations among marine areas around the island. From west to east, the former land-use zones used to stratify adjacent marine areas were: 1) NASD, 2) CA, 3) EMA and SIA, 4) LIA, and 5) ECA (Figure 1.4). It was decided to combine EMA and SIA into one strata as they appear to have been used for similar purposes (e.g., military training exercises besides ATG training).

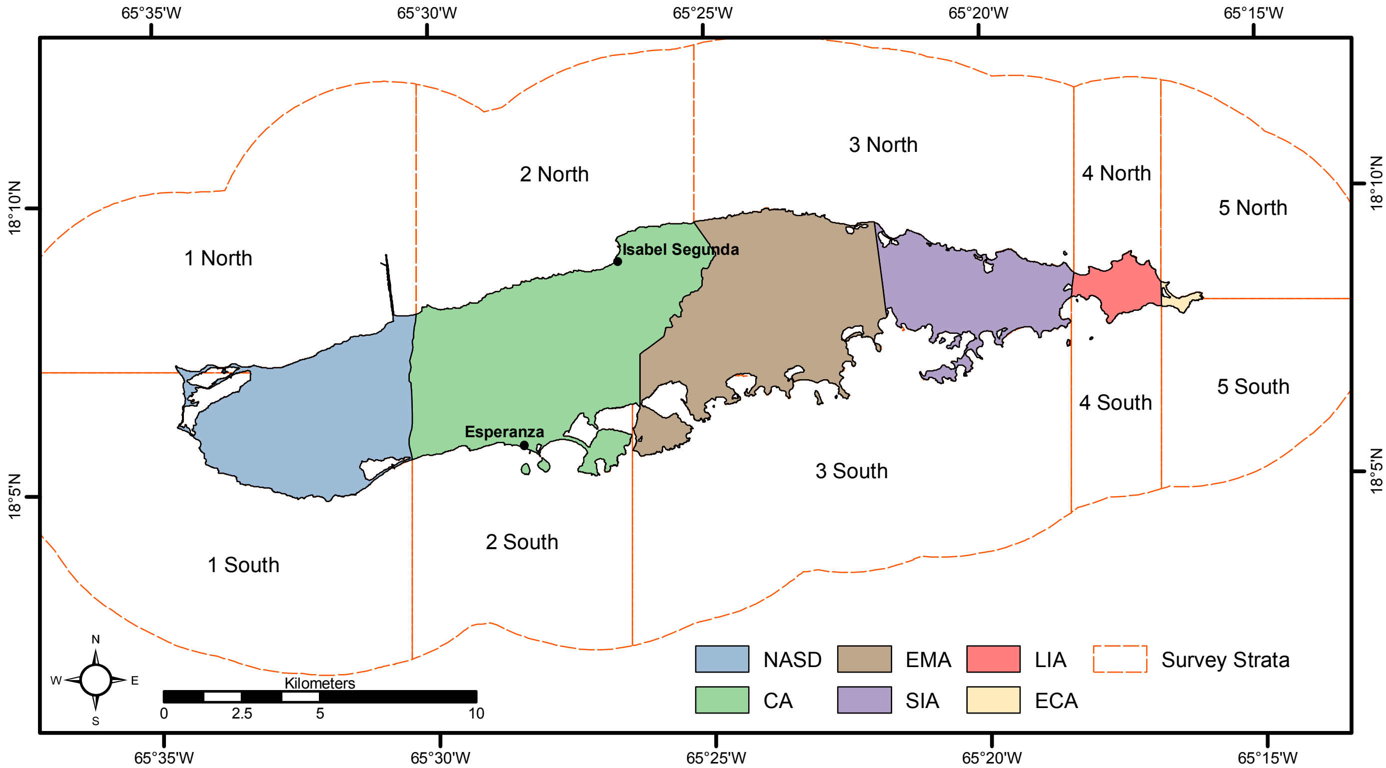


Figure 1.4. Sampling strata based on former ownership of lands on Vieques.

The overall objectives of this report were to 1) quantify differences in marine environments offshore from the various land-use zones, 2) compare environmental characteristics in Vieques to those available elsewhere in Puerto Rico and the U.S. Virgin Islands, and 3) establish baseline values to compare with future studies as land-use practices and resource conditions change around Vieques. Specific objectives of each chapter were as follows:

Chapter 2: Update and improve benthic habitat maps of Vieques. Relative to the latest comprehensive maps available, a smaller mapping unit (1000 versus 4000 m^2), more recent satellite and aerial imagery (2006-2008 versus 1999), and more detailed classification scheme were used.

Chapter 3: Characterize benthic and fish communities on hardbottom around Vieques, identify differences in communities adjacent to former land-use zones, and establish baseline values for change detection.

Chapter 4: Characterize the flora and fauna of selected lagoons and shelf areas including: Puerto Mosquito, Puerto Ferro, Ensenada Honda, and Puerto Negro.

Chapter 5: Characterize chemical contamination, differences in contamination based on former land-use, establish baseline values for change detection, and identify sites where sediment contamination exceeds established sediment quality guidelines.

Chapter 6: To characterize nutrient levels, north/south or east/west gradients in nutrient concentration, and to establish baseline values for change detection.

LITERATURE CITED

Barton, J.V., and J.W. Porter. 2004. Radiological, chemical, and environmental health assessment of the marine resources of the Isla de Vieques Bombing Range, Bahia Salina del Sur, Puerto Rico. Underwater Ordinance Recovery, Inc. and the University of Georgia Institute of Ecology. 44 pp.

Bauer, L.J., C. Menza, K.A. Foley, and M.S. Kendall. 2008. An ecological characterization of the marine resources of Vieques, Puerto Rico. Part I: Historical data synthesis. Prepared by National Centers for Coastal Ocean Science (NCCOS) Biogeography Branch in cooperation with the Office of Response and Restoration. Silver, Spring, MD. NOAA Technical Memorandum NOS NCCOS 86. 121 pp.

CH2M HILL. 2004. Draft final closure plan open burn/open detonation site, former Atlantic Fleet Weapons Training Facility Vieques, Puerto Rico. Prepared for Department of the Navy, Atlantic Division Naval Facilities Engineering Command. CTO Task Order 039, LANTDIV CLEAN III Program, Virginia Beach, VA.

Code of Federal Regulations. 2001a. Caribbean Sea and Vieques Sound, in vicinity of Eastern Vieques; bombing and gunnery target area. Title 33- Navigation and Navigable Waters, Volume 3, Chapter 2- Corps of Engineers, Department of the Army, Part 334- Danger Zone and Restricted Area Regulations. Section 334.1470.

Code of Federal Regulations. 2001b. Vieques Passage and Atlantic Ocean, off east coast of Puerto Rico and coast of Vieques Island; naval restricted areas. Title 33- Navigation and Navigable Waters, Volume 3, Chapter 2- Corps of Engineers, Department of the Army, Part 334- Danger Zone and Restricted Area Regulations. Section 334.1480.

DOI (U.S. Department of the Interior). 2007. Final comprehensive conservation plan/environmental impact statement for Vieques National Wildlife Refuge, Vieques, Puerto Rico. Fish and Wildlife Service, Southeast Region, Atlanta, GA.

DON (U.S. Department of the Navy). 1979. Draft environmental impact statement for the continued use of the Atlantic Fleet Weapons Training Facility Inner Range (Vieques). Prepared by TAMS (Tippetts, Abbett, McCarthy, Stratton) and Ecology and Environment, Inc.

DON (U.S. Department of the Navy). 1980. Final environmental impact statement for the continued use of the Atlantic Fleet Weapons Training Facility Inner Range (Vieques). Prepared by TAMS (Tippetts, Abbett, McCarthy, Stratton) and Ecology and Environment, Inc.

DON (U.S. Department of the Navy). 1986. Environmental assessment of continued use of the Atlantic Fleet Weapons Training Facility Inner Range, Vieques, Puerto Rico. Prepared by Ecology and Environment, Inc.

DON (U.S. Department of the Navy). 2001. Biological assessment for continuing training activities on the Inner Range Vieques, Puerto Rico. Contract No. N622470-95-D-1160, CTO 0015.

Federal Register 7182-7189. 2005. National priorities list for uncontrolled hazardous waste sites. Vol. 70, No. 28.

Garcia-Sais, J.R., R.L. Castro, J.S. Clavell and M. Carlo. 2001. Baseline characterization of coral reef and seagrass communities from Isla de Vieques, Puerto Rico. Department of Marine Sciences, University of Puerto Rico, Mayaguez. 108 pp.

GMI (Geo-Marine, Inc.). 2003. Reef ecosystem baseline assessment survey and monitoring, Vieques Island, Naval Station Roosevelt Roads, Puerto Rico. Prepared for Atlantic Division, Naval Facilities Engineering Command, Norfolk, Virginia. 341 pp.

GMI (Geo-Marine, Inc.). 2005. An assessment of the condition of coral reefs off the former Navy bombing ranges at Isla de Culebra and Isla de Vieques, Puerto Rico. Prepared for the Department of Defense, Legacy Resource Management Program, Arlington, Virginia, and US Army Corps of Engineers, Huntsville, Alabama. 76 + ix pp.

Langhorne, E. 1987. Vieques: History of a Small Island. The Vieques Conservation and Historical Trust. Vieques, PR. 90 + A4 pp.

Macintyre, I.G., B. Raymond and R. Stuckenrath. 1983. Recent history of a fringing reef, Bahia Salina del Sur, Vieques Island, Puerto Rico. Atoll Research Bulletin 268, Smithsonian Institution, Washington DC.

Rogers, C.S., G. Cintron and C. Goenaga. 1978. The impact of military operations on the coral reefs of Vieques and Culebra. Report to the Department of Natural Resources, San Juan, Puerto Rico.

CHAPTER 2: BENTHIC HABITATS OF VIEQUES, PUERTO RICO

Laurie J. Bauer[1,2,], Matthew S. Kendall[1], Adam G. Zitello[1,2], and Tim Battista[1]*

[1]Center for Coastal Monitoring and Assessment, National Centers for Coastal Ocean Science, National Ocean Service, NOAA, 1305 East-West Hwy, Silver Spring, MD 20910

[2]Consolidated Safety Services, Inc., Fairfax, VA 22030, under NOAA Contract No. DG133C07NC0616

[*]Corresponding author: laurie.bauer@noaa.gov

2.1 INTRODUCTION

This chapter describes the creation and assessment of benthic habitat maps for the nearshore waters of Vieques. The objective was to provide spatially-explicit information on the habitat types, biological cover and live coral cover of Vieques' coral reef ecosystem. These fine-scale habitat maps, generated by interpretation of 2006-2008 IKONOS imagery and orthophotography, represent a significant improvement from NOAA's previous digital maps of the U.S. Caribbean (Kendall et al. 2001) due to an expanded habitat classification scheme, smaller minimum mapping unit (MMU), and more recent imagery. The previous map NOAA map of Vieques was created using 1999 imagery with an MMU of one acre (~4047 m^2), while the new map was created with imagery collected in 2006-2008 with an MMU of 1000 m^2. A discussion of previous mapping efforts in Vieques can be found in Bauer et al. (2008).

The chapter consists of four primary components: 1) a description of the benthic habitat classification scheme used to classify habitats, 2) a discussion of the techniques used for map creation, 3) an assessment of the map accuracy, and 4) a summary of map statistics, habitat distributions, and deliverables. The maps will be used by managers and scientists for planning, research and monitoring activities, and will support the management and conservation of the marine waters of Vieques. The Vieques benthic habitat map and a suite of associated products are available to the public on a NOAA Biogeography Branch website devoted to this mapping effort (http://ccma.nos.noaa.gov/ecosystems/coralreef/vieques.html).

2.2 BENTHIC HABITAT CLASSIFICATION SCHEME

The Vieques habitat classification scheme defines benthic habitats based on five attributes: 1) broad geographic zone, 2) geomorphological structure type, 3) dominant biological cover, 4) degree of live coral cover,

Geographic Zone	Geomorphological Structure	Biological Cover	Percent Coral Cover	Percent Hardbottom
Land	Coral Reef and Hardbottom	**Major Cover**	0% - <10%	0% - <10%
Salt Pond	Rock/Boulder	Algae	10% - <50%	10% - <30%
Shoreline Intertidal	Aggregate Reef	Seagrass	50% - <90%	30% - <50%
Lagoon	Individual Patch Reef	Live Coral	90% - 100%	50% - <70%
Reef Flat	Aggregated Patch Reefs	Mangrove	Unknown	70% - <90%
Back Reef	Spur and Groove	Coralline Algae		90% - 100%
Reef Crest	Pavement	No Cover		Unknown
Fore Reef	Pavement with Sand Channels	Unknown		
Bask/Shelf	Reef Rubble	**Percent Major Cover**		
Bank/Shelf-Escarpment	Rhodoliths	10% - <50%		
Channel	Unknown	50% - <90%		
Dredged	Unconsolidated Sediment	90% - 100%		
Unknown	Sand	Unknown		
	Mud			
	Sand with Scattered Coral and Rock			
	Unknown			
	Other Delineations			
	Land			
	Artificial			
	Unknown			

Figure 2.1. The classification scheme defines benthic habitats with five primary attributes (described by separate boxes) and several hierarchical levels of classification therein.

and 5) percent hardbottom. A hierarchical structure of describing features at varying levels of detail was used so that numerous detailed habitats are encompassed by more broadly defined habitat classes. This hierarchy provides users with the ability to expand and collapse the detail of the habitat map to suit their needs. Every feature in the benthic habitat map is assigned a designation from each level of the scheme (Figure 2.1). The ability to apply any component of this scheme is dependent on being able to identify and delineate a given feature in remotely sensed imagery.

Many factors were considered in the development of this habitat classification scheme including: requests of the management community, existing classification schemes for coastal ecosystems, quantitative *in situ* habitat data, minimum mapping unit (MMU) and spectral limitations of remotely sensed imagery (Kendall et al. 2001). The habitat classification scheme used in Vieques was based on the evolution of schemes developed by NOAA in efforts to map the U.S. Caribbean and Pacific Islands (Kendall et al. 2001; Battista et al. 2007a,b). A very similar version of the scheme used here was also used in the recent mapping of St. John, USVI (Zitello et al. 2009), with the exception of an additional modifier for the Vieques map (i.e., percent hardbottom).

The primary difference between the new scheme and the one used by Kendall et al. (2001) in the previous mapping of Vieques is the separation of biological cover from habitat structure and additional detailed classes. Dominant biological cover, live coral cover, and percent hardbottom were not identified in the previously used scheme.

The new scheme is also improved in other ways as compared to the previous NOAA schemes used for benthic habitat mapping in the Pacific (e.g., Battista et al. 2007a,b). The primary difference was the deviation from coral-centric classification rules to a biological dominance scheme in which benthic habitats were classified based on the dominant biological cover type present on each feature. In previous NOAA coral reef habitat schemes, the biological cover component was assigned in a step-wise progression to first capture the presence of live coral and then attempt to classify any other biological cover if coral was not present. In other words, during map creation the interpreter would assign a polygon to the "Live Coral" biological cover class if there was 10% or greater live coral cover even if the polygon was predominantly covered by another biological cover type. For example, a patch reef covered by 15% live coral and 85% turf algae would be described in the previous classification schemes as "Live Coral 10% - <50%". This approach often mislead map users in over-stating the degree of live coral cover at the expense of the more prevalent biological cover type.

In NOAA's new Vieques habitat classification scheme, biological cover was described simply as the dominant cover type on each feature of the map. Percent cover of live coral was mapped separately in the Vieques scheme by the introduction of a new map attribute *Percent Coral Cover*. This attribute describes the percent live coral cover (includes "hard" scleractinians and "soft" gorgonians) for every feature. It is important to note that Percent Coral Cover refers only to the hardbottom component of any mapped polygon. For instance, an area of sand with some small scattered patch reefs in it could be classified as 10% - <50% live coral cover even though 90% of the polygon is bare sand.

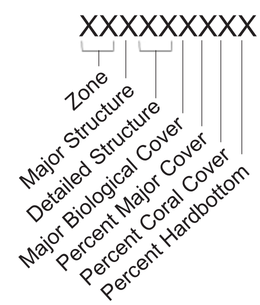


Figure 2.2. Schematic of each attribute's position in the UniqueID code of the classification scheme.

Every unique combination of classification attributes was provided a distinct identifier in the *UniqueID* field of the GIS layer. *UniqueID* consists of an 8-digit number string with each position in the string corresponding to a specific map attribute (Figure 2.2). Within each attribute, different classifications were assigned discrete numbers.

Geographic Zones

Thirteen mutually exclusive zones can be identified from land to open water corresponding to typical insular shelf and coral reef geomorphology. These zones include: *Land, Salt Pond, Shoreline Intertidal, Reef Flat, Lagoon, Back Reef, Reef Crest, Fore Reef, Bank/Shelf, Bank/Shelf Escarpment, Channel, Dredged, and Unknown*. Figures 2.3 – 2.5 illustrate zone types across typical cross-sections of the island shelf when the reef feature is either separated from shore by a lagoon (Figure 2.3), fringing the shore (Figure 2.4), or not emergent (Figure 2.5). Zone refers only to each benthic community's location and does not address substrate or biological cover types that are found within. For example, the *Lagoon* zone may include patch reefs and reef rubble; however, these are considered structural elements that may or may not occur within the lagoon zone and therefore, are not used to define it (Kendall et al. 2001). A brief description of each zone is provided in the following text.

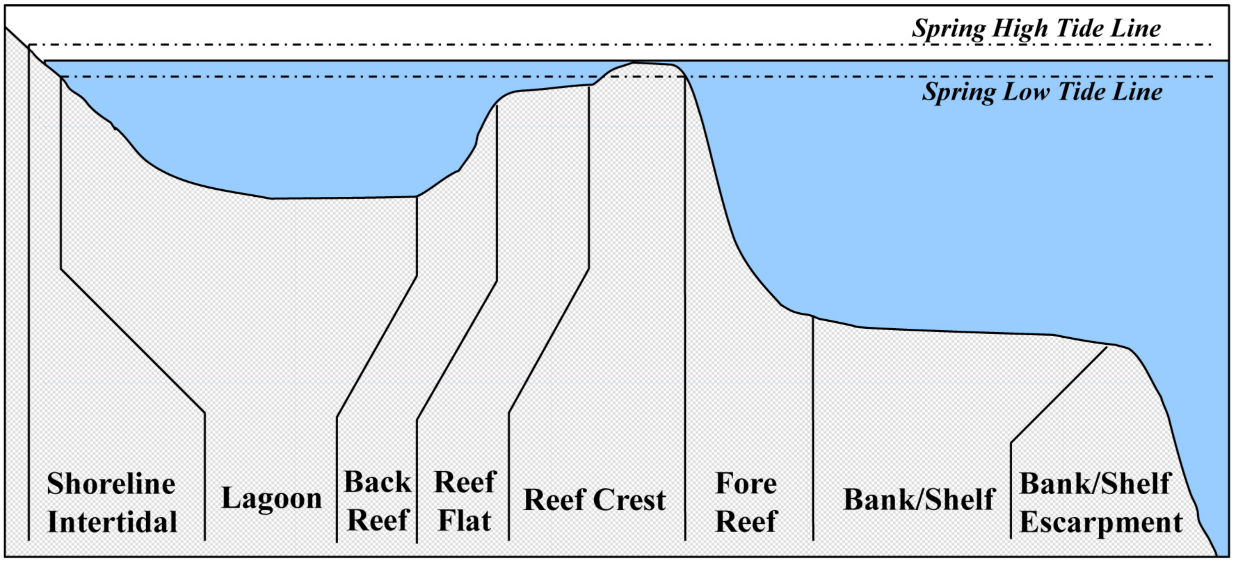


Figure 2.3. Cross-section of zone types where a barrier reef is present. Reef is separated from the shore by a relatively wide, deep lagoon.

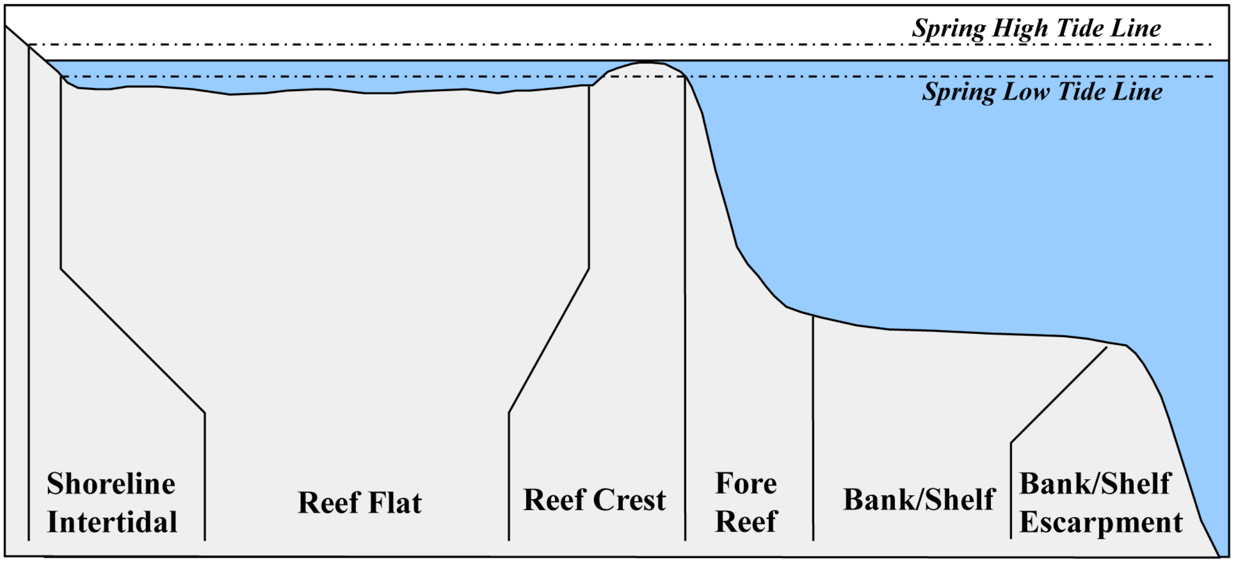


Figure 2.4. Cross-section of zone types where a fringing reef is present. Reef platform is continuous with the shore.

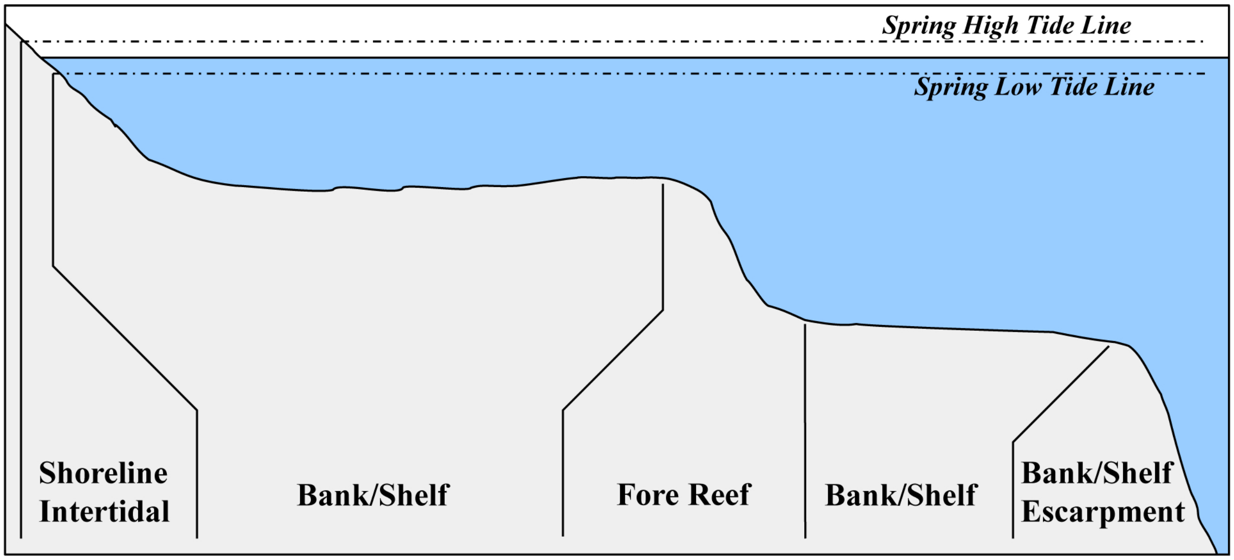


Figure 2.5. Cross-section of zone types where no emergent reef crest is present.

Land

Terrestrial features at or near the spring high tide line. Shoreline delineations describing the boundary between land and submerged zones are established at the wrack line where possible or the wet line at the time of imagery acquisition (Figure 2.6). (Unique ID = 10)


Figure 2.6. Depiction of shoreline delineations on unconsolidated (left) and rocky (right) coastlines. A red line highlights each shoreline on satellite imagery.

Salt Pond

Enclosed area just landward of the shoreline with a permanent or intermittent flooding regime of saline to hypersaline waters (Figure 2.7). When a mangrove fringe lined the inland water body, this was also included in the *Salt Pond* zone (as opposed to *Shoreline Intertidal* as described below). (Unique ID = 11)


Figure 2.7. Depictions of the *Salt Pond* zone just inshore of Purple Beach (left). A red polygon outlines the feature on satellite imagery. In Vieques, these features are typically lined by mangroves (right).

Shoreline Intertidal
Area between the spring high tide line (or landward edge of emergent vegetation when present) and lowest spring tide level. Emergent segments of barrier reefs are excluded from this zone and instead are defined below as *Reef Crest*. Typically, this zone is narrow due to the small tidal range in Puerto Rico (Figure 2.8). While present island-wide, the feature is often too narrow to be mapped on steep shorelines due to the scale of the imagery and the MMU. (Unique ID = 12)

Figure 2.8. Representation of two different types of *Shoreline Intertidal* zones. A low energy mangrove shoreline (left) and a high energy rocky shoreline (right) on the east end of Vieques.

Lagoon
Shallow area (relative to the deeper water of the bank/shelf) between the *Shoreline Intertidal* zone and the *Back Reef* of a reef or a barrier island. This zone is typically protected from the high-energy waves commonly experienced on the *Bank/Shelf* and *Reef Crest* zones (Figure 2.9). (Unique ID = 13)

Reef Flat
Shallow, semi-exposed area of little relief between the *Shoreline Intertidal* zone and the *Reef Crest* of a fringing reef. This broad, flat area often exists just landward of a *Reef Crest* and may extend to the shoreline or drop into a *Lagoon*. This zone is often somewhat protected from the high-energy waves commonly experienced on the *Bank/Shelf* and *Reef Crest* zones (Figure 2.10). (Unique ID = 14)

Figure 2.9. View of the *Lagoon* zone on satellite imagery at Playa Blanca. A red polygon outlines the feature.

Figure 2.10. Depictions of the *Reef Flat* zone on satellite imagery in Ensenada Honda. A red polygon outlines the feature.

Back Reef
Area just landward of a *Reef Crest* that slopes downward towards the seaward edge of a *Lagoon* floor or *Bank/Shelf*. This zone is present only when a *Reef Crest* exists. (Unique ID = 15)

Reef Crest
The flattened, emergent (especially during low tides) or nearly emergent segment of a reef. This high wave energy zone lies between the *Fore Reef* and *Back Reef* or *Reef Flat* zones. Breaking waves are often visible in overhead imagery at the seaward edge of this zone (Figure 2.11). (Unique ID = 16)

Fore Reef
Area along the seaward edge of the *Reef Crest* that slopes into deeper water to the landward edge of the *Bank/Shelf* platform (2.11). Features not associated with an emergent *Reef Crest* but still having a seaward-facing slope that is significantly greater than the slope of the *Bank/Shelf* are also designated as *Fore Reef* (Figure 2.4). (Unique ID = 17)

Bank/Shelf
Deeper water area (relative to the shallow water in a lagoon) extending offshore from the seaward edge of the *Fore Reef* or shoreline to the beginning of the escarpment where the insular shelf drops off into deep, oceanic water (Figure 2.11). If no *Reef Crest* is present, the *Bank/Shelf* is the flattened platform between the *Fore Reef* and deep open ocean waters or between the *Shoreline Intertidal* zone and open ocean. (Unique ID = 18)

Figure 2.11. A series of satellite images illustrating the transition from *Reef Crest* (left) to *Fore Reef* (middle) to *Bank/Shelf* (right) zones seaward of Puerto Negro. Each zone is depicted in color on the respective map.

Bank/Shelf Escarpment (19)
This zone begins on the oceanic edge of the *Bank/Shelf*, where depth increases rapidly into deep, oceanic water and exceeds the depth limit of features visible in optical imagery around Vieques. This zone is intended to capture the transition from the shelf to deep waters of the open ocean.

Channel (20)
Naturally occurring channels that often cut across several other zones.

Dredged (21)
Area in which natural geomorphology is disrupted or altered by excavation or dredging.

Unknown (99)
Zone indistinguishable due to turbidity, cloud cover, water depth, or other interference with an optical signature of the seafloor.

Geomorphological Structure Types

Fifteen distinct and non-overlapping geomorphologic structure types were described that can be mapped by visual interpretation of remotely-sensed imagery. Habitats or features that cover areas smaller than the MMU were not considered. For example, sand halos surrounding patch reefs are often too small to be mapped independently. Structure refers only to predominate physical composition of the feature and does not address location (e.g., on the shelf or in the lagoon). The structure types are defined in a collapsible hierarchy ranging

from four major classes (*Coral Reef and Hardbottom*, *Unconsolidated Sediment*, *Other Delineations*, and *Unknown*), to fifteen detailed classes (*Rock/Boulder, Spur and Groove, Individual Patch Reef, Aggregated Patch Reefs, Aggregate Reef, Reef Rubble, Pavement, Pavement with Sand Channels, Rhodoliths, Sand, Mud, Sand with Scattered Coral and Rock, Artificial, Land*, and *Unknown*).

Coral Reef and Hardbottom

Areas of both shallow and deep-water seafloor with solid substrates including bedrock, boulders and deposition of calcium carbonate by reef building organisms. Substrates typically lack a thick sediment cover, but a thin veneer of sediment may be present at times. Detailed structure classes within this category include *Rock/ Boulder, Spur and Groove, Individual Patch Reef, Aggregated Patch Reefs, Aggregate Reef, Reef Rubble, Pavement, Pavement with Sand Channels*, and *Rhodoliths*. (Unique ID = 1)

Rock/Boulder

A primarily continuous exposure of solid carbonate blocks or volcanic rock extending offshore from the island bedrock or aggregation of loose carbonate or volcanic rock fragments that have been detached and transported from their native beds (Figure 2.12). Individual boulders range in diameter from 0.25 – 3 m as defined by the Wentworth scale (Wentworth 1922). (Unique ID = 33)

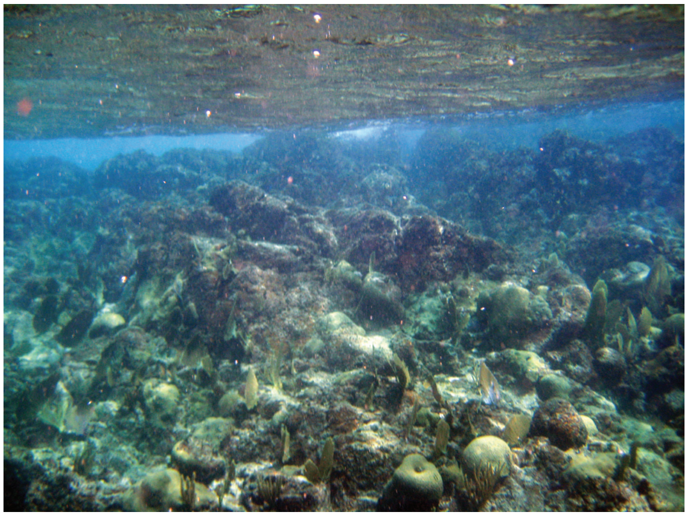
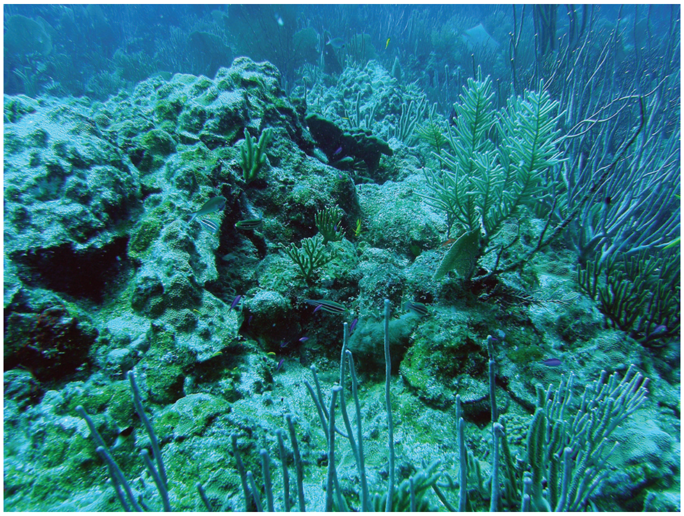


Figure 2.12. Depictions of *Rock/Boulder* structure in Vieques. A red polygon outlines the feature on satellite imagery.

Aggregate Reef

Continuous, high-relief coral formation of variable shapes lacking sand channels of *Spur and Groove*. Includes linear coral formations that are oriented parallel to shore or the shelf edge (Figure 2.13). This class is used for such commonly referred to terms as linear reef, fore reef or fringing reef. (Unique ID = 10)



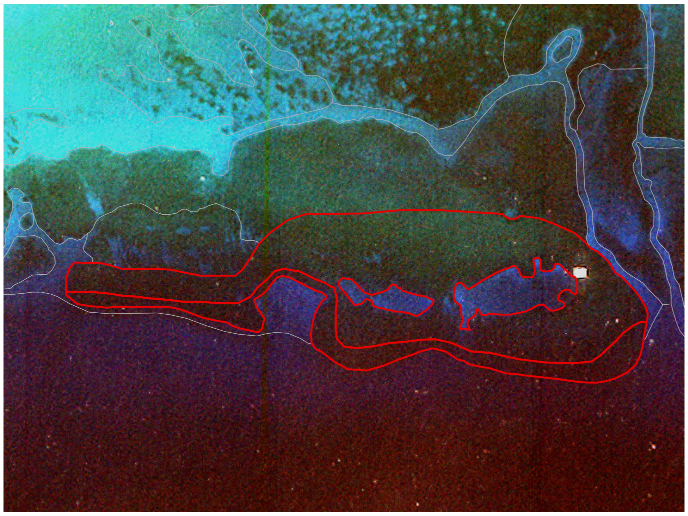


Figure 2.13. Depictions of *Aggregate Reef* structure in Vieques. A red polygon outlines the feature on satellite imagery.

Individual Patch Reef

Patch reefs are coral formations that are isolated from other coral reef formations by bare sand, seagrass, or other habitats and that have no organized structural axis relative to the contours of the shore or shelf edge. They are characterized by a roughly circular or oblong shape with a vertical relief of one meter or more in relation to the surrounding seafloor (Figure 2.14). *Individual Patch Reefs* are larger than or equal to the MMU. (Unique ID = 11)

Aggregated Patch Reefs

Having the same defining characteristics as an *Individual Patch Reef.* This class refers to clustered patch reefs that individually are too small (less than the MMU) or are too close together to map separately. Where aggregated patch reefs share sand halos, the halo is included in the polygon (Figure 2.14). (Unique ID = 12)

Figure 2.14. Comparison of patch reef delineations west of Isabel Segunda. Due to the influence of minimum mapping units, patch reefs of the same complex are designated by either *Individual Patch Reef* (left) or *Aggregated Patch Reefs* (right). Red polygons outline the features on satellite imagery.

Spur and Groove

Structure having alternating sand and coral formations that are oriented perpendicular to the shore or reef crest. The coral formations (spurs) of this feature typically have a high vertical relief relative to pavement with sand channels (Figure 2.15) and are separated from each other by 1-5 meters of sand or hardbottom (grooves), although the height and width of these elements may vary considerably (Figure 2.15). This habitat type typically occurs in the *Fore Reef* or *Bank/Shelf Escarpment* zone. (Unique ID = 13)

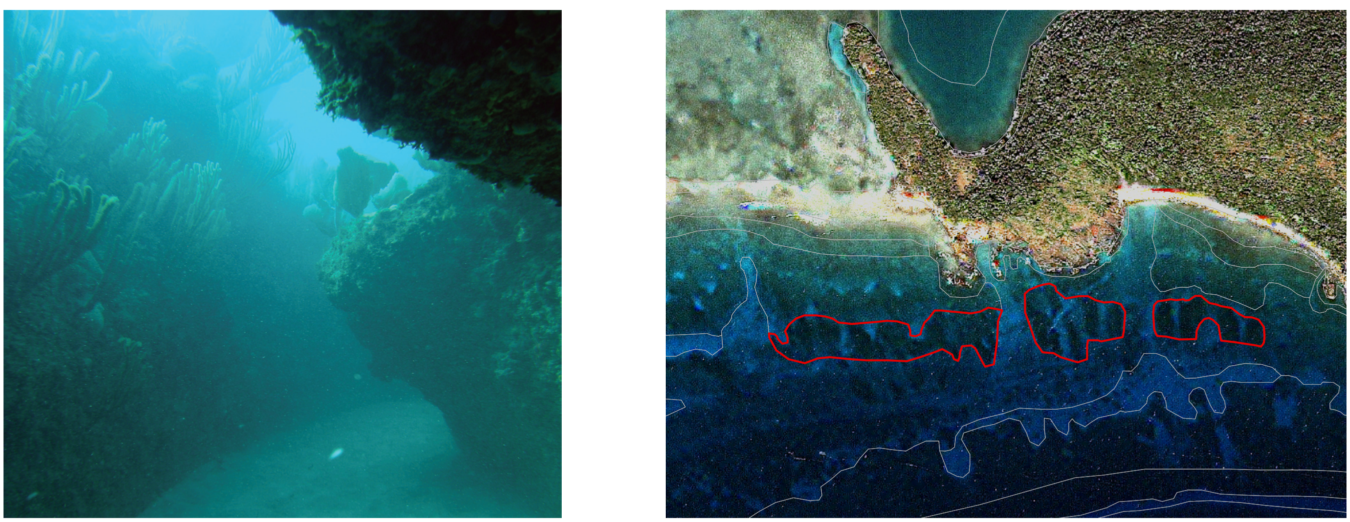


Figure 2.15. Depictions of *Spur and Groove* structure in Vieques. A red polygon outlines the features on satellite imagery, south of Punta Carenero.

Pavement

Flat, low-relief, solid carbonate rock in regularly broad areas with coverage of algae, hard coral, gorgonians, zooanthids or other sessile vertebrates that are dense enough to partially obscure the underlying surface (Figure 2.16). On less colonized *Pavement* features, rock may be covered by a thin sand veneer or turf algae. (Unique ID = 14)

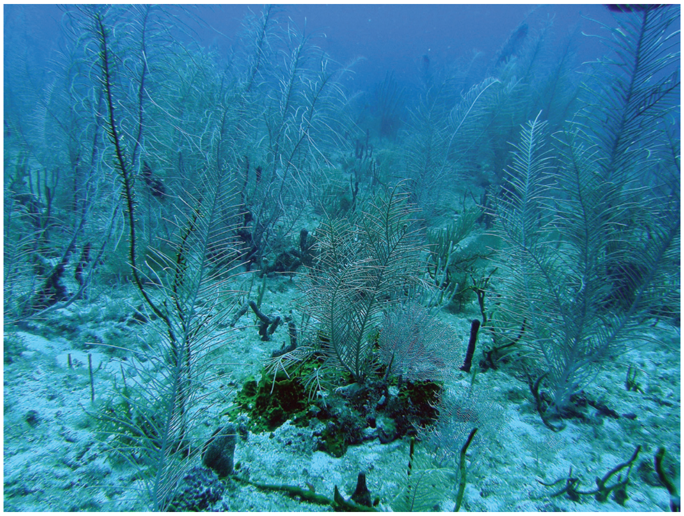
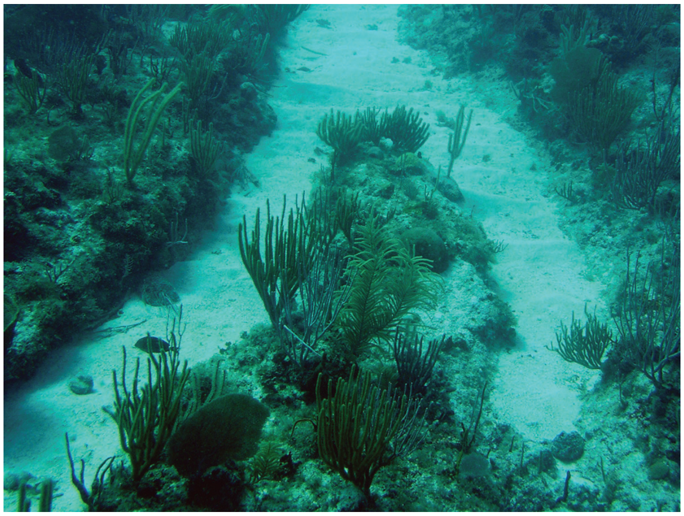


Figure 2.16. Depictions of *Pavement* structure in Vieques. A red polygon outlines the features on satellite imagery.

Pavement with Sand Channels

Habitats of pavement with alternating sand/surge channel formations that are oriented perpendicular to the shore or *Bank/Shelf Escarpment*. The sand/surge channels of this feature have low vertical relief relative to *Spur and Groove* formations. This habitat type occurs in areas exposed to moderate wave surge such as the *Bank/Shelf* zone (Figure 2.17). (Unique ID = 15)



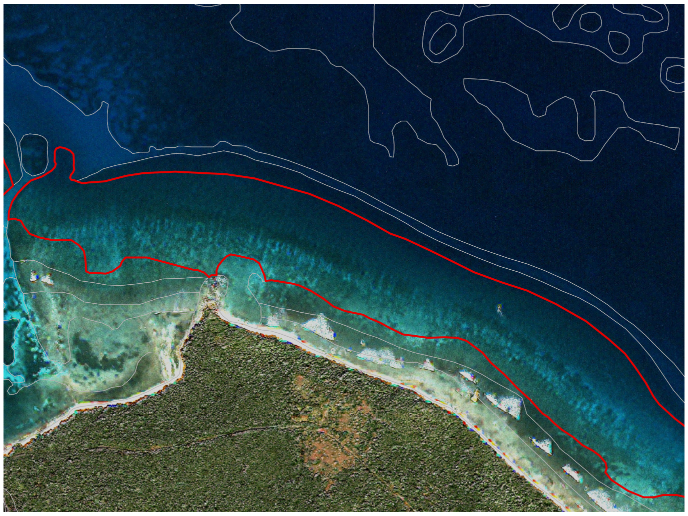


Figure 2.17. Depictions of *Pavement with Sand Channels* structure in Vieques. A red polygon outlines the features on satellite imagery.

Reef Rubble
Dead, unstable coral rubble often colonized with turf, filamentous or other macroalgae. This habitat often occurs landward of well developed reef formations in the *Reef Crest, Back Reef* or *Reef Flat* zones. Less often, *Reef Rubble* can occur in low density aggregations on broad offshore sand areas (Figure 2.18). (Unique ID = 16)

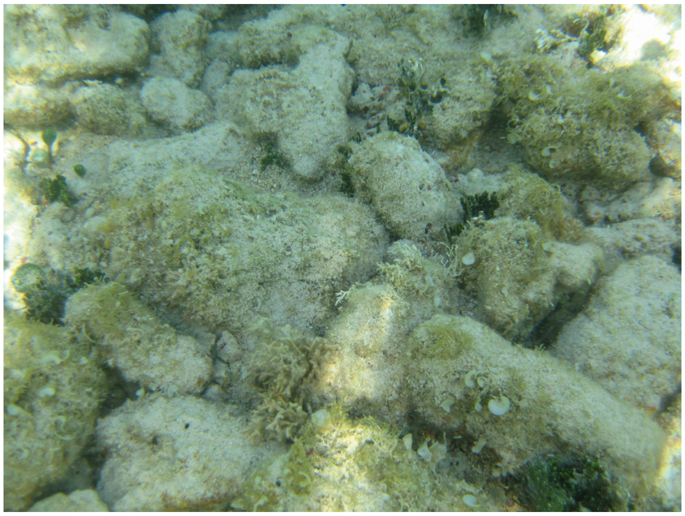


Figure 2.18. Depictions of *Reef Rubble* structure in Vieques. A red polygon outlines the features on satellite imagery.

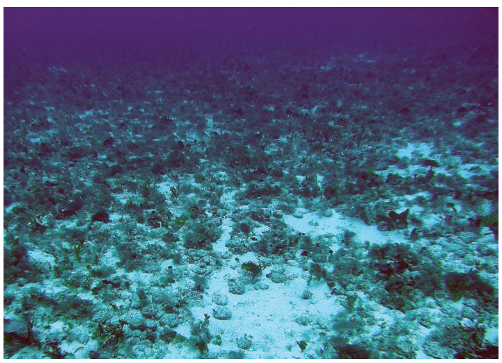
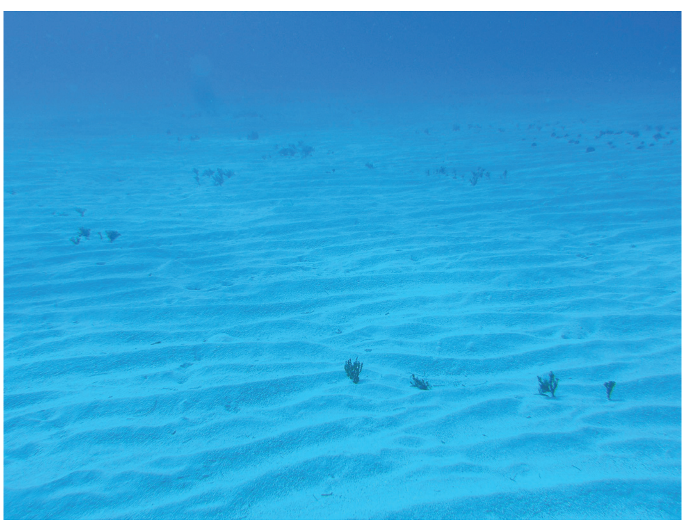


Figure 2.19. Typical *Rhodolith* bed north of Vieques.

Rhodoliths
Aggregation of cylindrical, discoidal, or irregular shaped calcareous nodules averaging approximately 6 cm in diameter. These unattached fragments are colonized by successive layers of coralline red algae. Commonly found in offshore topographic depressions (Figure 2.19). (Unique ID = 17)

Unconsolidated Sediment
Areas of the seafloor consisting of small particles (<.25 m) with less than 10% cover of large stable substrate. Detailed structure classes of softbottom include *Sand*, *Mud*, and *Sand with Scattered Coral and Rock*. (Unique ID = 2)

Sand
Coarse sediment typically found in areas exposed to currents or wave energy (Figure 2.20). Particle sizes range from 1/16 – 256 mm, including pebbles and cobbles (Wentworth 1922). (Unique ID = 18)



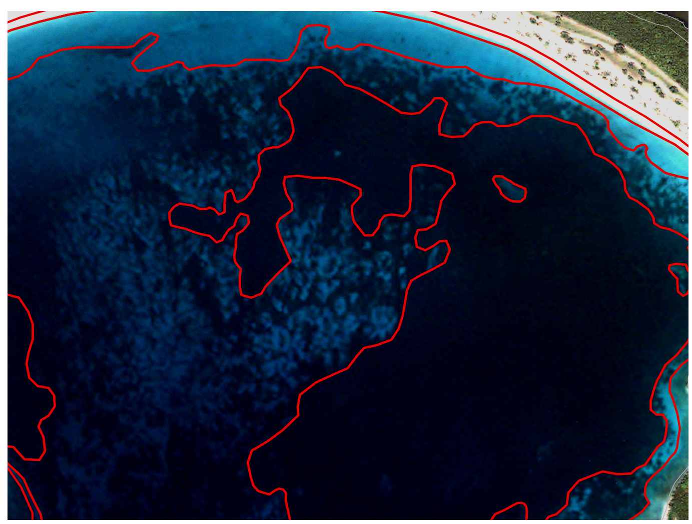


Figure 2.20. Depictions of *Sand* structure in Ensenada Sombe in Vieques. The features outlined by a red polygon include Sand with no biological cover (lighter), as well as with seagrass and algae (darker).

Mud
Fine sediment often associated with river discharge and build-up of organic material in areas sheltered from high-energy waves and currents (Figure 2.21). Particle sizes range from <1/256 – 1/16 mm (Wentworth 1922). (Unique ID = 19)

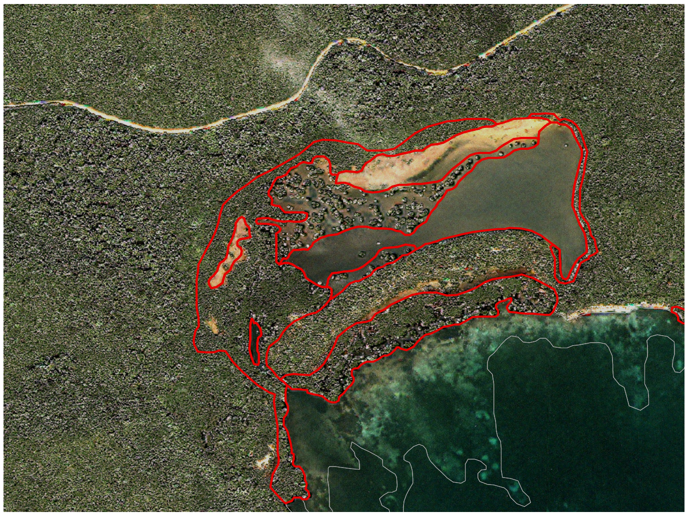



Figure 2.21. Depictions of *Mud* structure in Vieques. A red polygon outlines the features on satellite imagery.

Sand with Scattered Coral and Rock
Primarily sand bottom with scattered rocks or small, isolated coral heads that are too small to be delineated individually (i.e., smaller than individual patch reef) (Figure 2.22). If the density of small coral heads is greater than 10% of the entire polygon, this structure type is described as *Aggregated Patch Reefs*. (Unique ID = 20)

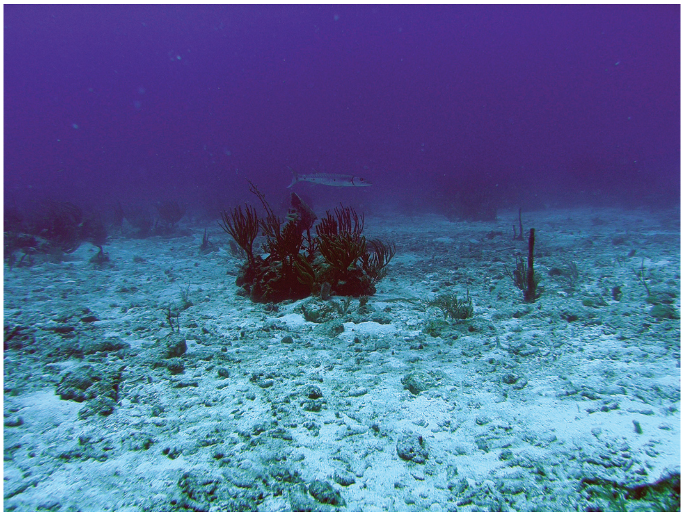
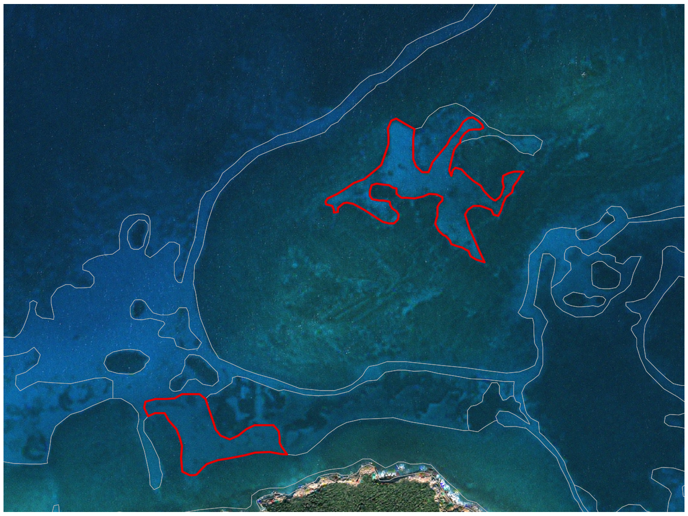



Figure 2.22. Depictions of *Sand with Scattered Coral and Rock* structure in Vieques. A red polygon outlines the features on satellite imagery.

Other Delineations
Any other type of structure not classified as *Coral Reef and Hardbottom* or *Unconsolidated Sediment*. Usually related to the terrestrial environment and/or anthropogenic activity. Detailed structure classes include *Land* and *Artificial*. (Unique ID = 3)

Land
Terrestrial features at or near the spring high tide line. (Unique ID = 21)

Artificial
Man-made habitats such as submerged wrecks, large piers, submerged portions of rip-rap jetties, and the shoreline of islands created from dredge spoil (Figure 2.23). (Unique ID = 22)

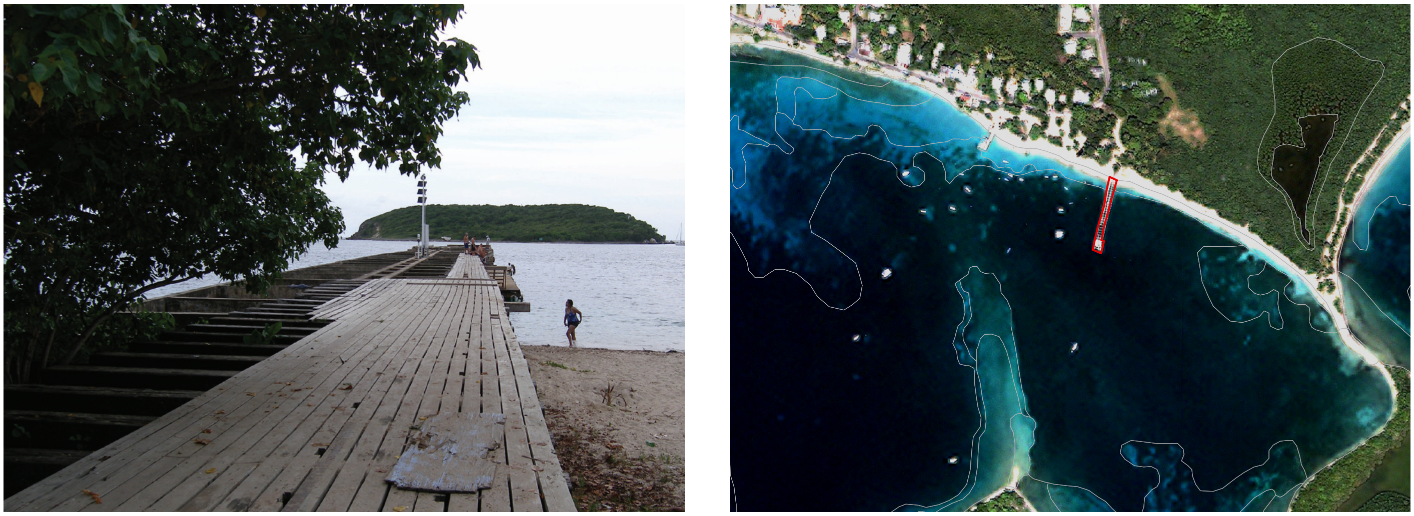


Figure 2.23. Depictions of the pier in Esperanza, an *Artificial* structure in Vieques. A red polygon outlines the feature on satellite imagery.

Unknown
Major structure indistinguishable due to turbidity, cloud cover, water depth, or other interference with an optical signature of the seafloor. (Unique ID = 9)

Unknown
Detailed structure indistinguishable due to turbidity, cloud cover, water depth, or other interference with an optical signature of the seafloor. (Unique ID = 99)

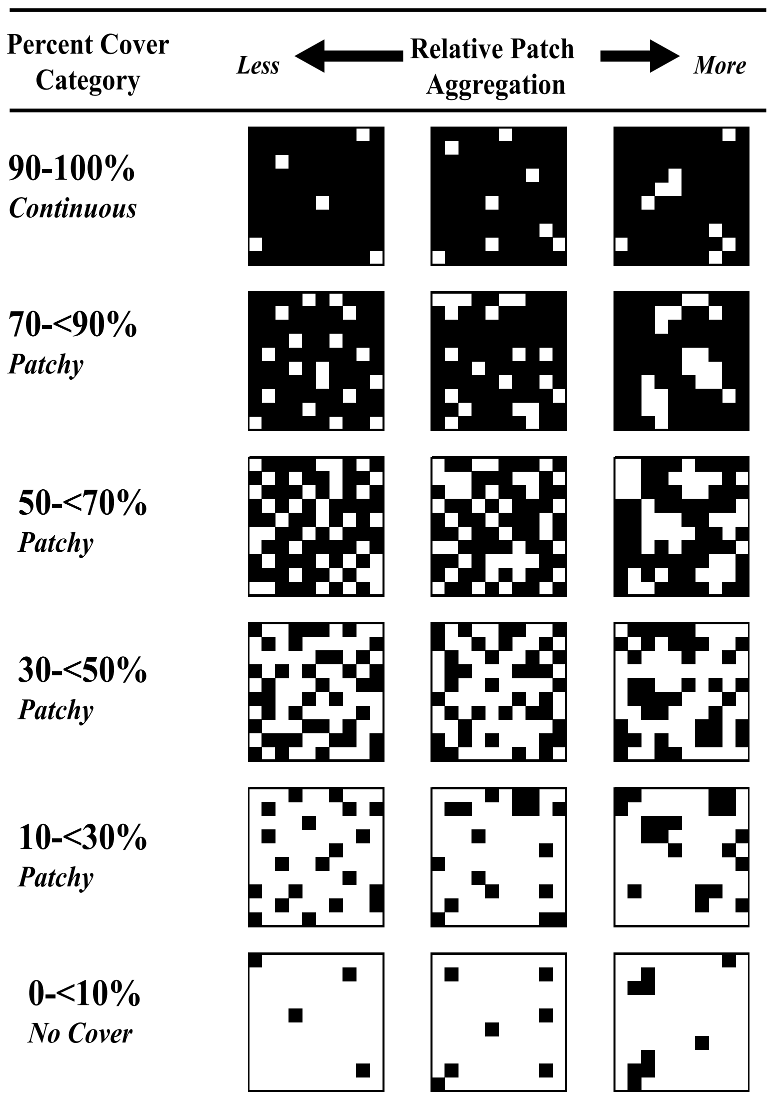


Figure 2.24. Guidance chart to aid visual interpreter's estimation of patchiness in assigning percent cover. Note that each large square denotes a minimum mapping unit.

Biological Cover Classes

Eighteen distinct and non-overlapping biological cover classes were identified that can be mapped through visual interpretation of remotely-sensed imagery. Cover classes refer only to the biological component colonizing the surface of the feature and does not address zone or structure type. Habitats or features that cover areas smaller than the MMU were not considered. The cover types are defined in a collapsible hierarchy ranging from seven major classes (*Algae, Seagrass, Live Coral, Mangrove, Coralline Algae, No Cover, Unclassified* and *Unknown*), combined with a modifier describing the distribution of the dominant cover type throughout the mapping unit (*10%-<50%, 50%-<90%, 90%-100%*).

It is important to reinforce that the modifier represents a measure of the level of patchiness of the biological cover at the scale of delineation and not the density observed by divers in the water. For example, a seagrass bed can be described as having 90%-100% biological cover, but have

sparse shoot densities when observed by divers. Figure 2.24 is a visual aid used by mappers to estimate of patchiness.

Major Cover

Algae

Substrates with 10% or greater distribution of any combination of numerous species of red, green, or brown algae. May be turf, fleshy or filamentous species. Occurs throughout many zones, especially on hard bottoms with low coral densities and soft bottoms in deeper waters on the *Bank/Shelf* zone (Figure 2.25). (Unique ID = 1)

Figure 2.25. Depictions of *Algae* dominated habitats. A red polygon outlines an algal-dominated feature in Puerto Ferro. Underwater pictures illustrate the different algal covers on unconsolidated sediment (middle) and hardbottom (right).

Seagrass

Habitat with 10% or more of the mapping unit dominated by any single species of seagrass (e.g., *Syringodium sp*., *Thalassia sp*., and *Halophila sp*.) or a combination of several species (Figure 2.26). (Unique ID = 2)

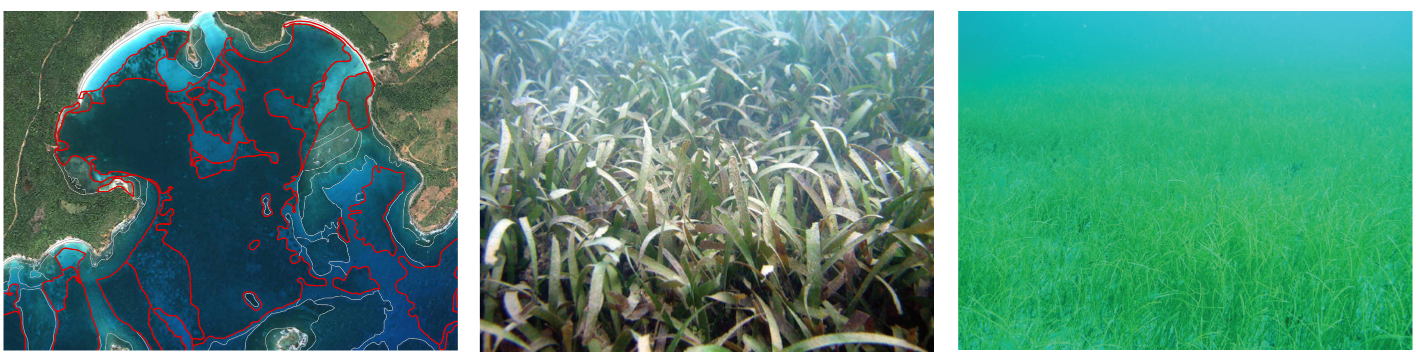


Figure 2.26. Extensive *Seagrass* beds, such as that in Bahia Salina del Sur, are prevalent around the island. A red polygon outlines the features on satellite imagery. Turtle Grass (*Thalassia testudinum*) (middle) and Manatee Grass (*Syringodium filiforme*) (right) are both common.

Live Coral

Substrates colonized with 10% or greater live reef building corals and other organisms including scleractinian (e.g., *Acropora sp.*) and octocorals (e.g., *Briareum sp.*). This category is rare in the U.S. Caribbean and was absent in Vieques. (Unique ID = 3)

Mangrove
Mangrove habitat is comprised of semi-permanently, seasonally or tidally flooded mangrove vegetation formations that grow near the sea (Figure 2.27). Mangrove trees are halophytes; plants that thrive in and are especially adapted to salty conditions. In Puerto Rico there are three species of mangrove trees: red mangrove *(Rhizophora mangle)*, black mangrove *(Avicennia germinans)*, and white mangrove *(Laguncularia racemosa)*; another tree, buttonwood *(Conocarpus erectus)* is often associated with the mangrove formation. Red mangrove grows at the water's edge and in the tidal zone. Black mangrove and white mangrove grow further inland in areas where flooding occurs only during high tides. Generally found in areas sheltered from high-energy waves. This habitat type is usually found in the *Shoreline Intertidal* zone. (Unique ID = 4)


Figure 2.27. Depictions of *Mangrove* cover in Ensenada Honda. A red polygon outlines the features on satellite imagery.

Coralline Algae
An area with 10% or greater coverage of any combination of numerous species of encrusting or coralline algae. May occur along the reef crest, in shallow back reef, and within the bank/shelf zone. Broad enough coverage to constitute dominant biological cover in a MMU is rare in the U.S. Caribbean. (Unique ID = 5)

No Cover
Substrates not covered with a minimum of 10% of any of the other biological cover types. This habitat is usually found on sand or mud bottoms. Overall, *No Cover* is estimated at 90%-100% of the bottom with the possibility of some very low density biological cover (Figure 2.28). (Unique ID = 6)

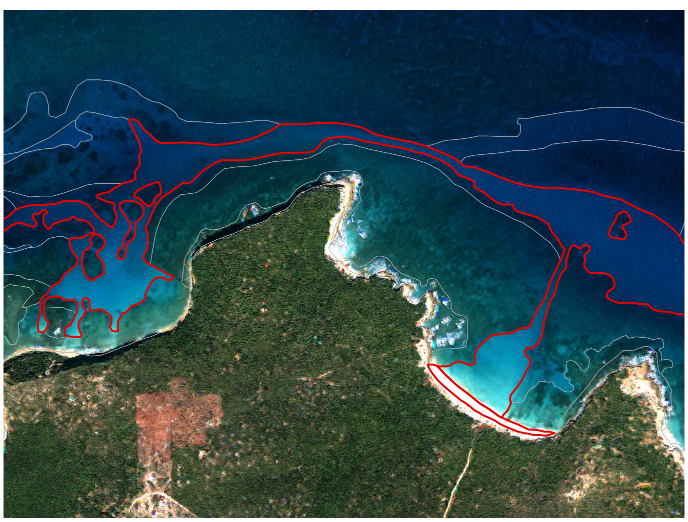
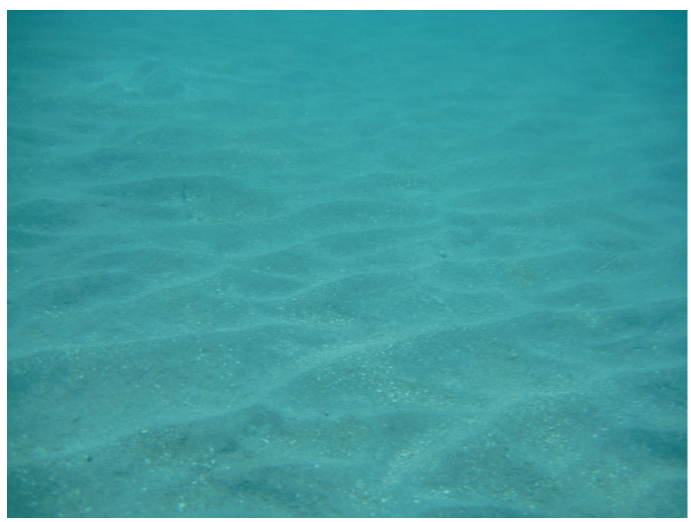



Figure 2.28. Depictions of features with *No Cover* on the northeast shore of Vieques. A red polygon outlines the features on satellite imagery.

Unclassified
A different biological cover type, such as upland, deciduous forest, that is not included in this habitat classification scheme. Most often used on polygons defined as *Land* with terrestrial vegetation. (Unique ID = 7)

Unknown
Biological cover is indistinguishable due to turbidity, cloud cover, water depth, or other interference with an optical signature of the seafloor. (Unique ID = 9)

Percent Major Cover

Patchy 10% - <50%
Discontinuous cover of the major biological type with breaks in coverage that are too diffuse to delineate or result in isolated patches of a different dominant biological cover that are too small (smaller than the MMU) to be mapped as a different feature. Overall cover of the major biological type is estimated at 10% - <50% of the polygon feature (Figure 2.29). (Unique ID = 2)

Patchy 50% - <90%
Discontinuous cover of the major biological type with breaks in coverage that are too diffuse to delineate or result in isolated patches of a different dominant biological cover that are too small (smaller than the MMU) to be mapped as a different feature. Overall cover of the major biological type is estimated at 50% - <90% of the polygon feature (Figure 2.29). (Unique ID = 3)

Continuous 90% - 100%
Major biological cover type covering 90% or greater of the substrate (Figure 2.29). May include areas of less than 90% major cover on 10% or less of the total area that are too small to be mapped independently (less than the MMU). (Unique ID = 4)

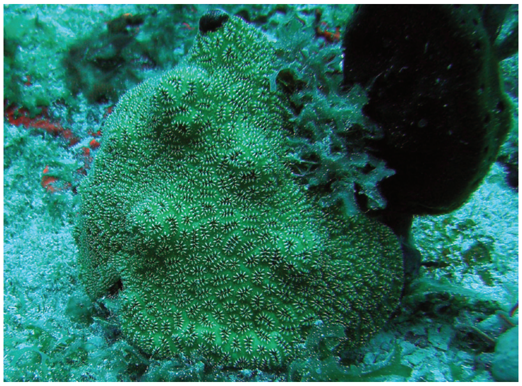
Figure 2.29. Representation of the three percent major cover modifiers (left to right: *10% - <50%, 50% - <90%, 90% - 100%*) using a seagrass bed in Bahia Salina del Sur as an example. Red polygons outline the features on satellite imagery.

Not Applicable
An estimate of percent cover is not appropriate for this particular major biological cover class. Regularly accompanies the use of *Unclassified* as the major biological cover. (Unique ID = 5)

Unknown
Percent estimate of the biological cover is indistinguishable due to turbidity, cloud cover, water depth, or other interference with an optical signature of the seafloor. (Unique ID = 9)

Live Coral Cover Classes

Four distinct and non-overlapping percent live coral classes were identified that can be mapped through visual interpretation of remotely-sensed imagery and ground-truthing. This attribute is an additional biological cover modifier used to maintain information on the percent cover of live coral, both scleractinian and octocorals (Figure 2.30), even when it is not the dominant cover type. In order to provide resource managers with additional information on this cover type of critical concern, four range classes were used (0% - <10%, 10% - <50%, 50% - <90%, 90% - 100%). Distinction of scleractinian coral versus octocoral (i.e., hard versus soft coral) was



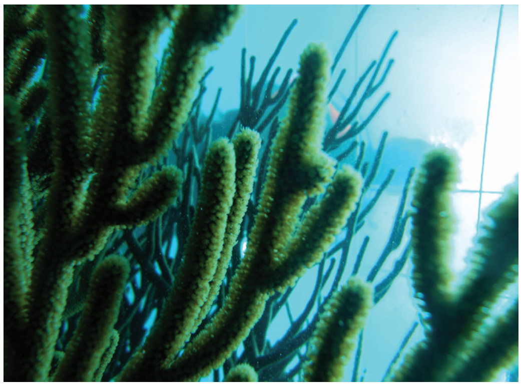


Figure 2.30. Both scleractinian (top) and octocorals (bottom) are considered when defining live coral cover.

limited by the current state of remote sensing technology and could not be separated in the Live Coral Cover modifier.

Live coral cover describes the percent coverage on hardbottom features at a fine-scale (i.e., diver scale), not the distribution at the scale of delineation, as was the case for dominant biological cover. For this reason, extensive *in situ* data is necessary. The observation was approximately 1 m to 3 m off the bottom feature and its associated field of view. As a result of these varying scales of interpretation, the percent biological cover and percent live coral cover modifiers are not additive properties within the same mapping unit. In many cases, they will sum to greater than 100%. For example, an aggregate reef can have continuous (90%-100%) cover of algae throughout a mapping unit, as well as 10%-50% density of coral at the fine-scale. Also, Percent Live Coral Cover refers only to the hardbottom component of any mapped polygon. For instance, an area of sand with some scattered coral and rock in it could be classified as 10% - <50% live coral cover even though 90% of the polygon is bare sand.

0% - <10%
Live coral cover of less than 10% of hardbottom substrate observed from 1-3 meters above the seafloor (Figure 2.31). (Unique ID = 1)

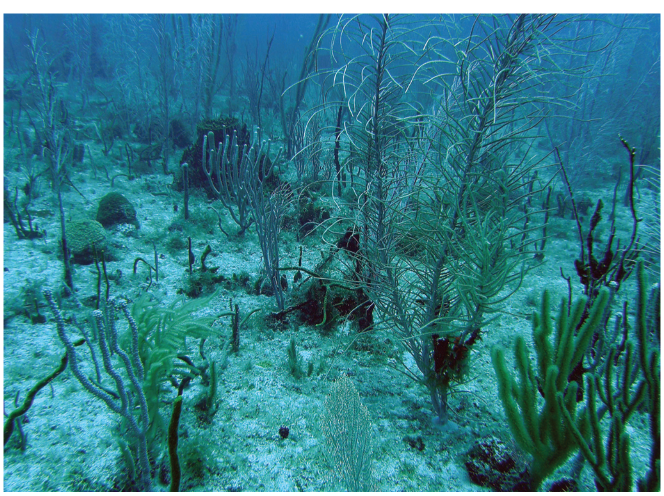
10% - <50%
Live coral cover between 10% and 50% of hard bottom substrate observed from 1-3 meters above the seafloor (Figure 2.31). (Unique ID = 2)

50% - <90%
Live coral cover between 50% and 90% of hard bottom substrate observed from 1-3 meters above the seafloor. (Unique ID = 3)

90% - 100%
Continuous live coral consisting of 90% or greater cover of the hard bottom substrate observed from 1-3 meters above the seafloor. (Unique ID = 4)

Not Applicable
An estimate of percent live coral cover is not appropriate for this particular feature. Regularly occurs in areas describing the terrestrial environment. (Unique ID = 5)

Unknown
Percent estimate of coral cover is indistinguishable due to turbidity, cloud cover, water depth, or other interference with an optical signature of the seafloor. (Unique ID = 9)



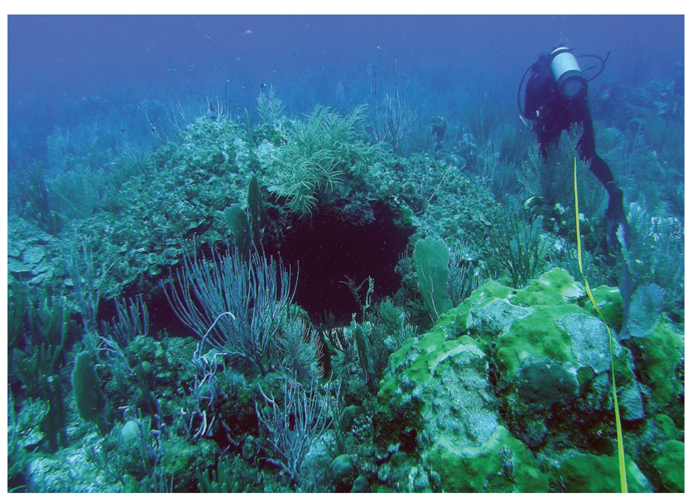


Figure 2.31. Illustration of live coral in the 0<10% (left), and 10% - 50% (right) cover range.

Percent Hardbottom Classes

An additional modifier was attributed to all polygons (except Land) to describe the percentage of hardbottom within that polygon. Several of the detailed structure types are heterogeneous in nature (e.g., *Aggregated Patch Reefs*, *Pavement w/ Sand Channels*, *Spur and Groove*), and the purpose of this modifier was to provide additional information about these structure types. It is expected that this will be useful in field survey planning when knowledge of the likelihood of encountering reef/hardbottom in an area is desired, or in estimating the actual amount of hardbottom in a polygon or mapped area. As with percent cover, Figure 2.24 was used as an aid to estimate the percent hardbottom in a polygon.

0% - <10%
Less than 10% of the structure within the polygon is hard substrate. All polygons attributed as *Unconsolidated Sediment* would have this designation. (Unique ID = 1)

10% - <30%
Hardbottom substrate between 10% and 30% of the polygon. (Unique ID = 2)

30% - <50%
Hardbottom substrate between 30% and 50% of the polygon. (Unique ID = 3)

50% - <70%
Hardbottom substrate between 50% and 70% of the polygon. (Unique ID = 4)

70% - <90%
Hardbottom substrate between 70% and 90% of the polygon. (Unique ID = 5)

90% - <100%
Hardbottom substrate between 90% and 100% of the polygon. (Unique ID = 6)

Not Applicable
An estimate of percent hardbottom is not appropriate for this particular feature. Regularly occurs in areas describing the terrestrial environment. (Unique ID = 7)

Unknown
Percent estimate of hardbottom is indistinguishable due to turbidity, cloud cover, water depth, or other interference with an optical signature of the seafloor. (Unique ID = 9)

2.3 MAP CREATION

Benthic habitat maps of the nearshore marine environment of Vieques, Puerto Rico were created by visual interpretation of remotely sensed imagery. Remotely sensed imagery, including IKONOS satellite imagery and color orthophotography, proved to be an excellent source from which to derive the edges, extent and attributes of marine habitats. Boundaries of features were delineated on digital imagery using a Geographic Information System (GIS) and a custom extension to ArcGIS 9.3 that enabled easy attribution of bottom features. Field investigations were conducted from small marine vessels in order to ground validate the spectral signature created by the myriad of submerged features of the marine environment. Once digital maps were produced, an assessment of thematic map accuracy was conducted.

General Mapping Approach

NOAA's approach to benthic habitat mapping of coral reef ecosystems was a six-step process:

1. Imagery Acquisition – The first step in map creation was the acquisition and processing of a comprehensive dataset of remotely sensed imagery. All imagery was geo-positioned to ensure acceptable spatial accuracy in the mapping product. In the case of Vieques two separate data types were used (IKONOS satellite imagery and color orthophotography) in order to capture the full mappable extent using optical techniques.

2. Habitat Boundary Delineation – A draft benthic habitat map was generated by delineating all features that could be identified by visual inspection of the remotely sensed imagery. During the creation of this first draft, the interpreter placed discrete points on the map that were difficult to distinguish and that warranted field investigation. These sites were referred to as "ground validation" positions.

3. Ground Validation – NOAA field scientists explored the ground validation locations with a suite of assessment techniques depending on the conditions at each site. A combination of underwater video, free diving, snorkeling and surface observations were used to survey the ecological characteristics at each location. This information was analyzed and the initial maps were edited to generate a second draft map.

4. Expert Review – The second draft map was then distributed to local marine biologists, resource managers, and other experts for review. Comments were integrated into the map products to generate a third draft map.

5. Accuracy Assessment – Field investigations were conducted at pre-defined locations to assess the accuracy of the third draft map. Locations were generated with a stratified random sampling design that allowed for a statistically rigorous assessment of map accuracy. An independent NOAA scientist, not associated with map creation, classified the video and conducted the analysis.

6. Final Products Creation – A final benthic habitat map for Vieques was generated by correcting inaccuracies identified by the accuracy assessment. Additionally, all associated datasets, including GIS files, field video and metadata were packaged and provided to project partners and the public.

Imagery Acquisition

Remote sensing imagery is a valuable tool for natural resource managers and researchers since they provide an excellent record of the location and extent of seafloor habitats. Generally, feature detection of seafloor habitats was possible from the shoreline to water depths of approximately 30 meters, depending on water clarity.

IKONOS satellite imagery provides precise and robust data with spectral and spatial resolution suitable for shallow water benthic mapping. Furthermore, satellite imagery provides efficient and effective global coverage for repeated imaging of remote islands that are often obscured by cloud cover. Ten scenes (Table 2.1) were obtained for the area extending approximately 3 nm from the shoreline of Vieques. The IKONOS satellite, owned and operated by GeoEye, provides commercially available panchromatic (black and white) and multispectral (blue/green/red/near-infrared) imagery. The panchromatic imagery has a 1 m pixel dimension and the multispectral imagery has a 4 m pixel dimension. The IKONOS imagery was acquired in 11 km wide swaths that are mosaicked together to produce complete images of locales.

Table 2.1. Acquisition dates of IKONOS satellite imagery used for creation of the Vieques benthic habitat map.

IMAGE ID	ACQUISITION DATE
215365_0000000	11/1/2006
215365_0040000	11/12/2006
215365_0070000	11/23/2006
215365_0120000	12/4/2006
215510_0000000	12/18/2006
244220_0000000	11/23/2007
244220_0010000	11/23/2007
255604_0000000	1/9/2008
259852_0040000	12/18/2007
260684_0010000	1/28/2008

The following four processing steps were completed for each IKONOS image and are described in detail in subsequent text:

1. Geo-positioned with satellite ephemeris data and supplemental ground control,

2. Corrected for terrain displacement,

3. Pan-sharpened, and

4. Removed sun glint.

Figure 2.32. Geodetic marker from NOAA's National Geodetic Survey that was used as a ground control point.

Geo-referencing of the imagery was performed using PCI OrthoEngine module. Fixed ground features visible in the IKONOS imagery (Figure 2.32) were selected for ground control points (GCPs) to be used in geo-referencing the imagery (i.e., to link the image pixels to a real world coordinate system). NOAA scientists occupied multiple locations throughout Vieques using L1 Trimble GeoXT mapping grade GPS. GPS observations were adjusted using the continuously-operating base station (VITH CORS) located in St. Thomas, USVI. NOAA obtained points with a wide distribution throughout the imagery whenever possible. Only ground control points for terrestrial features were collected due to the difficulty of obtaining precise positions for submerged features. Image to image tie-points were used to further co-register the imagery with other better positioned scenes. Tie points are distinct features, such as street intersections, piers, coral heads, reef edges, and bridges, which were visible in overlap areas of each image. These features were precisely aligned between scenes, thus providing exterior orientation control to co-register the scene.

Terrain displacement was corrected for the orthrectification bundle adjustment using the U.S. Geological Survey's Digital Elevation Model (DEM) (Figure 2.33).

PCI OrthoEngine Pansharpening module was employed to create a high-resolution color image to be used for visual interpretation by NOAA scientists. Pan-sharpening, also known as image fusion, is the concept of compiling multiple images into a composite product, which maintains the spectral signatures of the input color images while enhancing the spatial features with the input panchromatic image. It was applied to the IKONOS imagery to increase the spatial resolution of the 4 m multispectral data to the panchromatic data resolution of 1 m.

In addition, image enhancements were conducted on the positioned and pan-sharpened imagery to remove specular reflection from the sea surface. Reflection of solar radiation on non-flat water surfaces often results in areas of bright white sun glint in remotely sensed imagery. Typically, sun glint forms bands of white along wave edges on the windward side of nearshore environments. Sun glint can obscure bottom features and should be removed before habitat delineation. The method for removal of sun glint described in Hedley et al. (2005) was applied to the IKONOS imagery.

True-color (red/green/blue) and false-color (near-infrared) digital orthophotos for Vieques, PR, was the secondary imagery source used for delineating benthic habitats. Imagery was collected by 3001, Inc. under contract to the U.S. Army Corps of Engineers, in September and October of 2007 to produce orthophotos with a one foot ground sample distance (GSD). Flight height was maintained at 8,650 ft above ground level throughout the acquisition effort and was collected at 30% sidelap. For a more complete description of the product see the metadata report included with the project deliverables. As the data were collected primarily for terrestrial purposes, the coverage of the marine environment varied between photos. However, the high-resolution imagery was often very useful for delineating nearshore features.

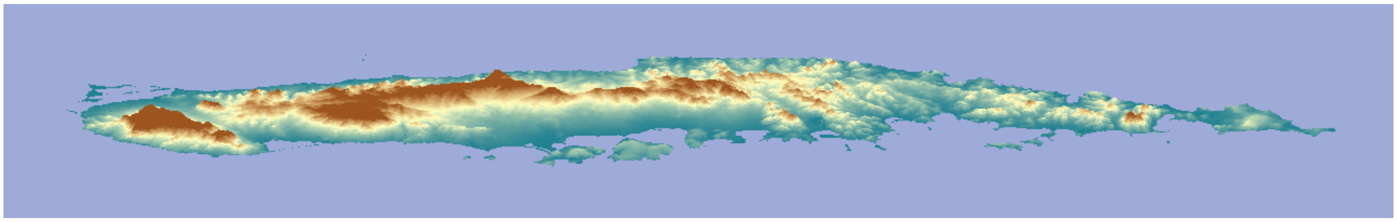


Figure 2.33. Oblique view of U.S. Geological Survey's Digital Elevation Model used to correct terrain displacement during orthorectification process.

Habitat Boundary Delineation and Attribution

As described by BAE Systems (2007), traditional methods of stereoplotter digitizing of photo interpreted habitat classes have gradually been replaced by the increased access and functionality of GIS software for on-screen "heads up" digitizing. GIS-based techniques have several distinct advantages, including:

- Elimination of intermediate steps required to go from hardcopy to digital maps, which reduces slight distortions in habitat boundaries,
- Enhanced productivity in map creation due to gained efficiency,
- Development of a dynamic link between habitat delineations and the associated attributes in a database, and
- Increased analytical capabilities through the use of spatial analysis routines in the GIS.

The Vieques benthic habitat map and mapping methods were developed using ESRI's ArcGIS 9.3 (ESRI 2008) and an ArcGIS extension created by NOAA, the Habitat Digitizer Extension (Buja 2008a). The Habitat Digitizer Extension is a GIS tool designed to use a hierarchical classification scheme to delineate features by visually interpreting geo-referenced images. The extension allowed the interpreter to create the custom classification scheme described in section 2.2, digitize polygons using standard ArcGIS editing tools, and attribute the features using a dialog containing the created scheme. The extension allowed for rapid delineation and attribution of polygons, which significantly improved the efficiency of map creation.

The Habitat Digitizer Extension allowed several critical digitizing parameters to be set in advance in order to standardize the map output. The Minimum Mapping Unit (MMU) restriction was set to 1,000 m^2 (~0.25 acre). In contrast, NOAA's previous map of PR and the USVI was created with a one acre MMU (Kendall et al. 2001). This reduction was in response to the coral reef management community's interest in having finer resolution maps to make resource management decisions with. However, there were still features visible in the imagery, such as patch reefs, which were smaller than the MMU and were not included as individual features in the map.

The digitizing scale was set to 1:4,000.The interpreter was allowed to zoom in and out to varying scales when assessing an area, but always returned to 1:4,000 before boundary delineation. Qualitative experimentation results adapted from Kendall et al. (2001) indicated that digitizing at this scale optimized the tradeoff between positional accuracy of lines and time spent digitizing. In general, line placement conducted while zoomed in at fine scales results in excellent line accuracy and detail, but can be quite time consuming. Conversely, while zoomed out, lines can be drawn quickly but lack both detail and positional accuracy. In addition, the resolution of the imagery often influences the digitizing scale. For example, when zooming in on a feature, there becomes a scale at which the feature becomes less distinct. Although the smaller pixel size of the orthophotos could have allowed mapping at a finer scale, as in Zitello et al. 2009, who used a 1:2000 scale, 1:4000 was more appropriate for the lower resolution IKONOS imagery.

Habitat boundary delineation and attribution techniques were adopted from Kendall et al. (2001). Using the Habitat Digitizer, habitat boundaries were delineated around spectral signatures of particular color and texture patterns in the remotely sensed imagery that corresponded to habitat types in the classification scheme described in Section 2.2. (Figure 2.34). This was often accomplished by first digitizing a large boundary polygon such as the habitats that compose the shoreline and then appending new polygons to the initial boundary polygon. Another technique was to draw one large polygon around a feature of similar type and then split it down into smaller polygons, an approach often used for seagrass beds of varying patchiness. It was believed that the positional accuracy of polygon boundaries was similar to that of the source imagery since delineations were performed directly on the remotely sensed imagery.

Brightness, contrast and histogram stretching of the source imagery were often manipulated in ArcGIS to enhance the interpretability of some subtle features and boundaries. This was particularly helpful in deeper water where differences in color and texture between adjacent features tend to be more subtle and boundaries more difficult to detect. Particular caution was used when interpretation was performed from altered images, since results from color and brightness manipulations can sometimes be misleading. Additional ancillary datasets were consulted to improve the understanding of particular areas. These data types included previously-com-

pleted habitat maps (Kendall et al. 2001), bathymetry, nautical charts, and imagery from different time periods.

Ground Validation

The creation of high-quality benthic habitat maps requires field work to enhance accuracies of habitat attribution and habitat delineation. Following the generation of an initial draft benthic habitat map, a team of NOAA scientists explored selected field locations to verify habitat type. These “ground validation” (GV) sites were targeted by the interpreter to satisfy one of the following two objectives:

1. Explore areas in the imagery with confusing or difficult to determine spectral signatures, or

2. Establish a transect moving from land to sea to better understand habitat transitions in a given area. These transects are important because a single habitat type may provide a different signature depending on water depth and sea state.

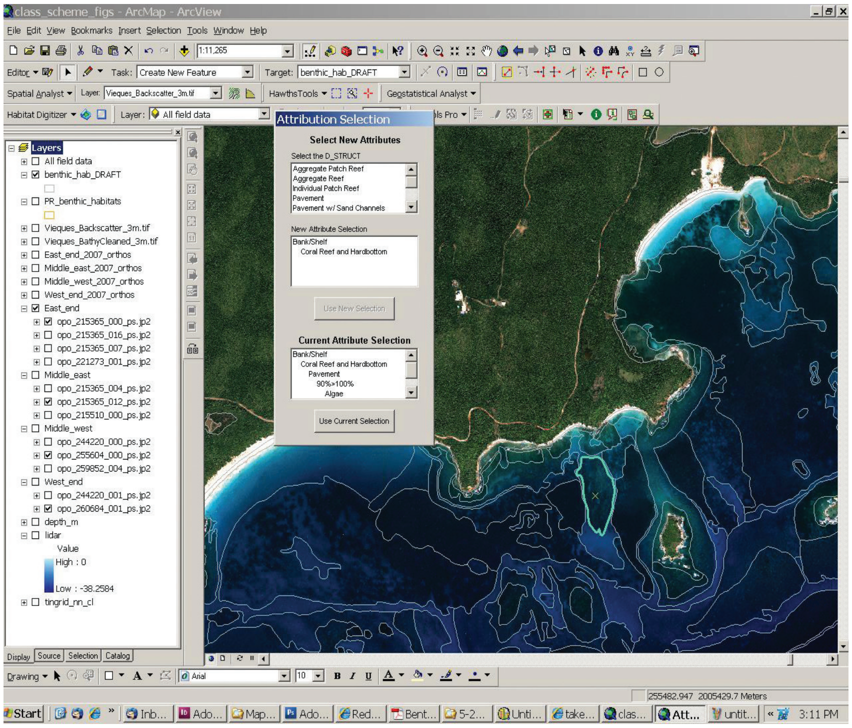


Figure 2.34. NOAA Biogeography Branch’s Habitat Digitizer Extension (Buja 2008a) was used to attribute map polygons with all components of the habitat classification scheme.

Numerous GV locations were selected while the photo interpreter was generating the draft habitat map. Geographic coordinates were extracted for these sites and uploaded into Garmin GPS 76 WAAS-enabled handheld devices. Data were collected on 141 GV sites (Figure 2.35) over a one-week field mission from October 7-13, 2008 (Section 2.4).

The boat captain maneuvered the vessel to within 5 m of the target location and made every effort to maintain that location without jeopardizing crew and equipment safety. Once on site, NOAA scientists would simultaneously deploy a SeaViewer Sea-Drop 950 camera and begin logging a waypoint on a Trimble GeoXT GPS receiver. The drop camera reached the bottom in approximately 5 - 10 seconds and bottom imagery was recorded to mini-digital video tapes using a Sony Walkman video recorder. The camera operator adjusted the camera position to get a downward view at approximately 2 m from the bottom and a side view of the habitat at each location. This allowed for accurate measurements of percent biological cover and a broader sense of the structure at each site. No attempt was made to standardize the amount of bottom time the camera would capture in order to avoid the confusion of viewing multiple habitat types. In fact, it was often advantageous for the vessel to drift across habitat transitions, thus allowing the interpreter to understand the ecotone at many locations. Position logging in the Trimble receiver was optimized to plot every epic (i.e., position) along a waypoint. This allowed for accurate depiction of the vessel’s drift line at a single GV location and was utilized in subsequent assessment of the data.

While the video camera was recording, an observer viewed the video real-time on a Panasonic Toughbook aboard the survey vessel. They categorized each site according to the levels of the habitat classification scheme: major and detailed geomorphological structure, major biological cover, percent major biological cover and percent coral cover. Data was entered into a custom data dictionary generated in Trimble Pathfinder Office software and loaded onto the Trimble data logger. Field sheets representing an exact replicate of the digital data dictionary were also populated as back-up to the digital classification information.

Of the 141 sites occupied during ground validation, 123 were assessed with the underwater drop camera. Shallow, nearshore sites that were inaccessible by the survey vessel were surveyed by snorkel. Sites were categorized in the same way, but in lieu of drop camera video, a digital camera in an underwater housing was used to take pictures. Mangrove target locations were generally assessed from the boat after approaching the

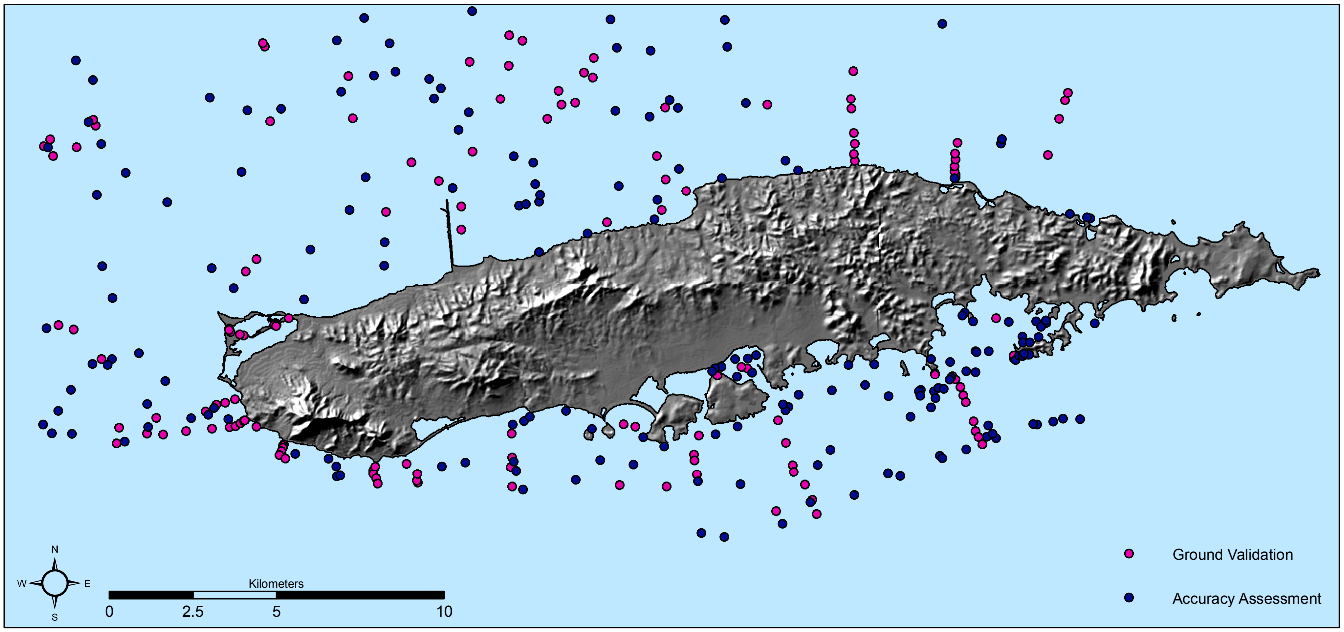


Figure 2.35. Spatial distribution of the 141 ground validation and 185 accuracy assessment sites visited during the October 2008 mission.

target as close as possible, and were again documented with digital pictures. Additional mangrove locations were approached by road.

Trimble Pathfinder Office software was used to post process and differentially correct the raw GPS data to the Continually Operating Reference System (CORS) station at St. Thomas, U.S. Virgin Islands (VITH). Videos were converted to digital video clips using Final Cut Pro software and reviewed. Precise GPS positions and the associated classification data were viewed in a GIS to enhance the accuracy of the draft benthic habitat map. Polygon boundaries and habitat classifications were revised where field data necessitated changes.

GIS Quality Control

All GIS deliverable products generated throughout the mapping process were closely examined for error. Particular attention was given to polygon geometry of the benthic habitat map and attribution of both the habitat map and GV and AA field GIS datasets. Multipart, sliver and void polygons were all removed using standard ArcGIS Spatial Analyst tools. Two custom ArcGIS extensions were employed to identify the following conditions:

1. Adjacency – polygons that shared a common boundary and exact attribute combination that were delineated separately (Buja 2008b),

2. Overlap – polygons sharing the same geographic space, thus violating mutual exclusion (Buja 2008c).

Errors resulting from either of these GIS routines were corrected on draft maps and eliminated in the final product.

A review of habitat boundaries by a NOAA staff member not involved in imagery interpretation concluded that all areas mapped as *Unknown* were indeed indistinguishable on the source imagery.

A visual inspection of attributes on a feature-by-feature basis was conducted to correct for any misspellings or illogical attribute combinations. These types of errors were minimal; as the use of the Habitat Digitizer Extension standardized the process of populating GIS attribute tables. In the rare instances where manual attribution was required, particular attention was given to control these processes. The aforementioned visual inspection accounted for any potential errors.

GIS data from this work were determined to be topologically clean and free of attribution errors. In addition, metadata summaries were prepared in an FGDC-compliant format for all GIS products that were supplied during final delivery.

2.4 ACCURACY ASSESSMENT

Thematic accuracy of the Vieques benthic maps was characterized for major and detailed geomorphological structure, major and detailed biological cover, percent hardbottom and percent coral cover.

Collection of Field Data

Sites for the accuracy assessment procedure were determined through a stratified random sampling technique. Funding and logistical constraints indicated that 185 sites could be included (Figure 2.35). Points were initially distributed based on the proportion of area occupied by each of the 12 detailed structure categories in a draft benthic map of Vieques. Classes that covered a large proportion of the total area but are easy to interpret had some points redistributed to other bottom classifications. For example, sand comprised ~60% of the mapped area and could therefore have received 60% of the assessment effort. Experience has shown, however, that *Sand* is relatively easily and accurately mapped (>90% correct, Battista et al. 2007a; Walker and Foster 2009; Zitello et al. 2009). Therefore, the assessment effort was redistributed to other important bottom types that covered less area. For example, *Aggregate Reef* covered only 4% of the mapped area and therefore initially only received 4% or 7 of the 185 available survey points. Survey effort was raised to 20 points to more adequately assess this scientifically and ecologically important bottom type. Points were randomly placed within each class at a minimum distance of 50 m apart to minimize potential overlap among survey sites.

Data were collected during a one-week field mission from October 6-13, 2009. Navigation to sample locations was conducted using GPS. Underwater video was taken at each site, provided the location was safely accessible by the survey vessel. Video length depended on the habitat type and vessel drift and ranged from approximately 30 seconds to two minutes. Videos of large, homogeneous sand habitats were generally short while heterogeneous hardbottom habitats, especially edges, were typically longer. While the video was being recorded, a string of GPS waypoints were recorded on board the vessel. At least three positions were logged at each site, but this number was generally much higher and depended on the satellite signal, length of the video clip, current speed, and vessel drift. This resulted in a string of positions that tracked boat movement at each site. Video at each site was categorized for major/detailed geomorphological structure, major/detailed biological cover, percent hardbottom, and percent coral cover.

Very shallow, nearshore sites were often not accessible by the survey vessel and video camera system and therefore were surveyed using snorkeling gear and a digital camera. Mangrove sites were generally assessed from the boat or land after approaching the target as close as possible.

Evaluation of Assessment Data

The GPS positions were determined to have a positional accuracy of < 1 m for most points. For each survey site, multiple GPS positions were combined to generate an "average" GPS point. The GPS data were then exported and plotted in ArcGIS along with the corresponding field notes. In most cases, the average point was a sufficient representation of the survey site; however in some cases vessel drift caused the survey to cross polygon edges. In these cases, the "average" survey point was shifted to the portion of the transect and polygon that was intended to be assessed.

Each video clip or digital picture was viewed in concert with the benthic habitat map and the remote sensing imagery of each site. All analysis at this stage was made by a photointerpreter independent of the scientist who created the benthic map. Patchiness of the biological cover was assessed at the polygon level, and hence it was often necessary to adjust the classifications that were initially recorded in the field to reconcile the differences between the video and map scales. For example, a site may have been classified as continuous seagrass based on the video clip alone, but if the patchiness of the polygon in which the site occurred was actually only 50% - <90% upon examination of the imagery, the patchiness for the survey point was changed to 50% - <90%. Similar adjustments were sometimes necessary to correctly characterize detailed structure. For example, heterogeneous hardbottom classes, such as *Pavement with Sand Channels*, could not always be correctly classified from the video alone if the vessel/video did not drift over a sand channel. In other cases, ad-

ditional information on the position, size and shape of hardbottom features was needed to determine whether the structure should be classified as *Aggregate Reef* or a *Patch Reef*.

Following these adjustments, the map classification underlying each point was extracted. Sites that differed between field notes and map classification were further evaluated both in GIS and from video to determine possible sources of disagreement. At this stage, mismatches between GPS and map attributes that were a product of the differences in scale between the video data and imagery rather than errors in classification were identified. For example, there were several occurrences where the survey video documented *Sand* with no cover, but the point was located within a heterogeneous polygon that was mapped as sand with patchy *Seagrass* or *Algae*, *Sand with Scattered Coral and Rock*, or *Aggregated Patch Reefs* that could only be perceived at the broad scale of the remote sensing imagery. For these cases, the points were only classified for structure based on both the video and imagery. Since the mapped polygon cover was not observed in the accuracy assessment video, they were not included in the assessment of biological cover.

Percent coral cover was classified for both hardbottom and softbottom habitats; however it is defined as the percent coral cover on the hardbottom substrate within that polygon (see Section 2.2). If a site was determined to be located within a hardbottom polygon but no hardbottom was seen in video (e.g., *Aggregated Patch Reefs*), coral cover could not be sufficiently assessed at that site. Hence, such sites were not included in the error matrix for percent coral cover.

Following this process, 185 points were included in the accuracy assessment analysis for major structure, 182 for detailed structure, 183 for major biological cover and detailed biological cover, 185 for percent hard bottom, and 185 for percent coral cover.

Analysis of Thematic Accuracy

The thematic accuracy of the Vieques benthic habitat map was characterized in several ways from these data. Error matrices were computed for the attributes major and detailed geomorphological structure, major and detailed biological cover, percent hard bottom, and percent coral cover. Overall accuracy, producer's accuracy, and user's accuracy were computed directly from the error matrices (Story and Congalton 1986). The error matrices were constructed as a square array of numbers arranged in rows (map classification) and columns (accuracy assessment, or ground-truthed classification). The overall accuracy (P_o) was calculated as the sum of the major diagonal (i.e., correct classifications), divided by the total number of accuracy assessment samples.

The producer's and user's accuracies were calculated to characterize the classification accuracy of individual map categories. The producer's accuracy is a measure of how well the mapper classified a particular habitat (e.g., the percentage of times that substrate ground-truthed as sand was correctly mapped as sand). The user's accuracy is a measure of how often map polygons of a certain habitat type were classified correctly (e.g., the percentage of times that a polygon classified as sand was actually ground-truthed as sand). Each diagonal cell in the matrix was divided by the column total (n_{i-}) to yield a producer's accuracy and by the row total (n_{-j}) to yield a user's accuracy.

In addition, the Tau coefficient (T_e), a measure of the improvement of classification accuracy over a random assignment of map categories, was calculated. As the number of categories increases, the probability of random agreement (Pr) diminishes, and T_e approaches P_o. See Ma and Redmond (1995) for mathematical equations.

Redistribution of sampling effort caused rare but important map categories to be sampled at a greater rate than common map categories. For example, although Sand habitat comprised 60% of the map area, only 25% of the target points were allocated for this habitat. Conversely, *Aggregate Reef* comprised only 4% of the map area, but received 11% of the allocated target sample points. Such allocation is necessary for reasonable assessment of individual map categories but introduced bias when assessing overall accuracy (Hay 1979; Card 1982). The bias introduced by differential sampling rates was removed using the method of Card (1982), which utilizes the proportional areas of each map category relative to the total map area. The category proportions were also utilized in the computation of confidence intervals (CI) for the overall, producer's, and user's accuracies (Card 1982; Congalton and Green 1999). This approach was modeled after Walker and Foster (2009), who recently conducted an accuracy assessment of a benthic map of the Florida Keys.

The category proportions (π_j) were computed from the GIS layer of the draft benthic habitat map by dividing the area of each category by the total map area. Proportions were not computed for the percent coral cover matrix. Due to the way percent coral cover was estimated, doing so would have required an adjustment by the percent hardbottom, and there was insufficient sample size of all combinations of the percent coral and percent hardbottom categories. The individual cell probabilities were computed as the product of the original error matrix cell values and π_j, divided by the total number of assessment points per category ($n_{\cdot j}$).

The relative proportions of the cell values within a row of the error matrix were unaffected by this operation, but the row total of a particular category now equaled the fraction of map area occupied by that category (π_j), instead of the total number of accuracy assessment points within it ($n_{\cdot j}$). The estimated true proportions (p_i) of each map category given the observed classification errors were computed as the sum of individual cell probabilities down each column of the error matrix.

The π_j-adjusted overall and producer's accuracies were then computed from the new error matrix. The values of the π_j-adjusted overall and producer's accuracies differ by design from those of the original error matrix, as they have been corrected for the areal bias introduced by stratified random sampling and the effort redistribution protocol. The user's accuracy, in contrast, is not affected. The variances and confidence intervals of the overall, producer's, and user's accuracies were then computed using the equations of Card (1982).

Accuracy Assessment Results and Discussion

Major Geomorphological Structure

Error matrices for major geomorphological structure are displayed in Table 2.2 for the simple tally of assessment points and 2.3 for the unbiased values of producers and overall accuracy corrected by category proportions. The overall accuracy (P_o) when calculated by a simple tally of correct points was 98.4% (Table 2.2). The Tau coefficient was 0.968 ± 0.036. Adjusted overall accuracy, corrected for bias using the map category proportions, was 99.1 (±0.0)% (Table 2.3). The user's and producer's accuracies were similarly high for both hard and softbottom habitats (Table 2.3).

Table 2.2. Error matrix for major geomorphological structure.

Map data (j)	Accuracy Assessment (i): Hard	Soft	$n_{\cdot j}$	User's Accuracy (%)
Hard	**109**	3	112	**97.3%**
Soft		**73**	73	**100.0%**
$n_{i\cdot}$	109	76	n=185	
Producer's Accuracy (%)	**100.0%**	**96.1%**	**P_o =**	**98.4%**
			T_e =	**0.968 ± 0.036**

Table 2.3. Error matrix for major geomorphological structure, using individual cell probabilities. The overall accuracy and producer's accuracy were corrected for bias using the category proportions.

Map data (j)	Accuracy Assessment (i): Hard	Soft	$\pi_{\cdot j}$	User's Accuracy (%)	User's CI (±%)
Hard	**0.325**	0.009	0.334	**97.3%**	**3.1%**
Soft		**0.666**	0.666	**100.0%**	**0.0%**
p_i	0.325	0.675	π=1		
Producer's Accuracy (%)	**100.0%**	**98.7%**	**P_o =**	**99.1%**	
Producer's CI (±%)	**0.0%**	**1.5%**	**CI(±) =**	**0.0%**	

Detailed Geomorphological Structure

Error matrices for detailed geomorphological structure are displayed in Table 2.4 for the simple tally of assessment points and 2.5 for the unbiased values of producers and overall accuracy corrected by category proportions. The overall accuracy (P_o) when calculated by a simple tally of correct points was 78.0%, with a Tau coefficient (T_e) of 0.760 ± 0.066 (Table 2.4). The adjusted overall accuracy, corrected for bias using the category proportions, was higher at 88.8 (±4.2)% (Table 2.5), because the classes that covered the most area were also the most correctly interpreted.

Accuracies for individual map categories must be interpreted cautiously due to the low sample sizes (<10 points). User's accuracy was above 70% for 7 of the 12 categories (Table 2.5). Categories with relatively low accuracies that were evaluated by an adequate number of points were *Individual Patch Reef* (42.9%) and *Sand with Scattered Coral and Rock* (61.5%). Both these categories had very large confidence intervals. *Individual Patch Reefs* were most often confused with *Pavement* due to the small and circular shape of some pavement patches on the NW side of Vieques. *Sand with Scattered Coral and Rock* was most often misclassified simply as *Sand*, a very similar bottom type that often occurs adjacent to areas

Table 2.4. Error matrix for detailed geomorphological structure.

Accuracy Assessment (i)

Map data (j)	Aggregate Reef	Aggregated Patch Reefs	Individual Patch Reef	Spur and Groove	Pavement	Pav w/ Sand Channels	Rock/Boulber	Reef Rubble	Rhodolith	Sand w/ SCR	Sand	Mud	$n_{\cdot j}$	User's Accuracy (%)
Aggregate Reef	**14**			1	3	1	1						20	**70.0%**
Aggregated Patch Reefs		**5**			1								6	**83.3%**
Individual Patch Reef	1	1	**6**		5					1			14	**42.9%**
Spur and Groove				**2**			1						3	**66.7%**
Pavement	2	2			**36**	2	3	1					46	**78.3%**
Pav w/ Sand Channels	3				2	**4**				1			10	**40.0%**
Rock/Boulder							**5**						5	**100.0%**
Reef Rubble					1			**3**			1		5	**60.0%**
Rhodoliths									**3**				3	**100.0%**
Sand w/ SCR										**8**	5		13	**61.5%**
Sand											**40**	1	41	**97.6%**
Mud												**16**	16	**100.0%**
$n_{i\cdot}$	20	8	6	3	48	7	10	4	3	10	46	17	n=182	
Producer's Accuracy (%)	**70.0%**	**62.5%**	**100.0%**	**66.7%**	**75.0%**	**57.1%**	**50.0%**	**75.0%**	**100.0%**	**80.0%**	**87.0%**	**94.1%**	P_o =	**78.0%**

T_e = 0.760 ± 0.066

Table 2.5. Error matrix for detailed geomorphological structure, using individual cell probabilities. The overall accuracy and producer's accuracy were corrected for bias using the category proportions.

Accuracy Assessment (i)

Map data (j)	Aggregate Reef	Aggregated Patch Reefs	Individual Patch Reef	Spur and Groove	Pavement	Pav w/ Sand Channels	Rock/Boulber	Reef Rubble	Rhodolith	Sand w/ SCR	Sand	Mud	$\pi_{\cdot j}$	User's Accuracy (%)	User's CI (±%)
Aggregate Reef	**0.028**			0.002	0.006	0.002	0.002						0.0404	**70.0%**	**20.49%**
Aggregated Patch Reefs	0.000	**0.005**			0.001								0.0054	**83.3%**	**30.43%**
Individual Patch Reef	0.001	0.001	**0.008**		0.007					0.001			0.0186	**42.9%**	**26.45%**
Spur and Groove				**0.000**									0.0001	**66.7%**	**54.43%**
Pavement	0.005	0.005			**0.081**	0.005	0.007	0.002					0.1040	**78.3%**	**12.16%**
Pav w/ Sand Channels	0.006				0.004	**0.008**				0.002			0.0203	**40.0%**	**30.98%**
Rock/Boulder							**0.004**						0.0037	**100.0%**	**0.00%**
Reef Rubble					0.010			**0.030**			0.010		0.0494	**60.0%**	**43.82%**
Rhodoliths									**0.093**				0.0925	**100.0%**	**0.00%**
Sand w/ SCR										**0.030**	0.019		0.0488	**61.5%**	**26.99%**
Sand											**0.581**	0.015	0.5959	**97.6%**	**4.82%**
Mud												**0.021**	0.0208	**100.0%**	**0.00%**
$p_{i\cdot}$	0.040	0.010	0.008	0.002	0.109	0.015	0.013	0.032	0.093	0.033	0.610	0.035	π=1		
Producer's Accuracy (%)	**70.3%**	**43.7%**	**100.0%**	**1.7%**	**74.7%**	**55.4%**	**29.8%**	**92.9%**	**100.0%**	**89.9%**	**95.3%**	**58.8%**	P_o =	**88.8%**	
Producer's CI (±%)	16.8%	29.8%	0.0%	3.6%	14.1%	33.8%	20.2%	13.9%	0.0%	13.1%	3.4%	47.8%	CI(±) =	**4.2%**	

with scattered coral or rock. Four categories had low adjusted producer's accuracy but were evaluated by very few accuracy assessment points and confidence intervals were large (Table 2.5).

Table 2.6. Error matrix for major biological cover.

Map data (j) \ Accuracy Assessment (i)	Algae	Live Coral	Mangrove	Seagrass	No Cover	$n_{\cdot j}$	User's Accuracy (%)
Algae	**120**	2		3	1	126	**95.2%**
Live Coral						0	**n/a**
Mangrove			**10**			10	**100.0%**
Seagrass	10			**20**		30	**66.7%**
No Cover					**17**	17	**100.0%**
$n_{i\cdot}$	**130**	**2**	**10**	**23**	**18**	n=183	
Producer's Accuracy (%)	**92.3%**	**0.0%**	**100.0%**	**87.0%**	**94.4%**	**P_o =**	**91.3%**

T_e = 0.891±0.051

Table 2.7. Error matrix for major biological cover, using individual cell probabilities. The overall accuracy and producer's accuracy were corrected for bias using the category proportions.

Map data (j) \ Accuracy Assessment (i)	Algae	Live Coral	Mangrove	Seagrass	No Cover	$\pi_{\cdot j}$	User's Accuracy (%)	User's CI (±%)
Algae	**0.4179**	0.0070		0.0104	0.0035	0.439	**95.2%**	**3.8%**
Live Coral						0.000	**n/a**	**n/a**
Mangrove			**0.0106**			0.011	**100.0%**	**0.0%**
Seagrass	0.1597			**0.3194**		0.479	**66.7%**	**17.2%**
No Cover					**0.0715**	0.071	**100.0%**	**0.0%**
$p_{i\cdot}$	0.578	0.007	0.011	0.330	0.075	π=1		
Producer's Accuracy (%)	**72.4%**	**n/a**	**100.0%**	**96.8%**	**95.4%**	**P_o =**	**81.9%**	
Producer's CI (±%)	**10.4%**	**n/a**	**0.0%**	**3.6%**	**8.8%**	**CI(±) =**	**8.4%**	

Major Biological Cover

Error matrices for major biological cover are displayed in Table 2.6 for the simple tally of assessment points and 2.7 for the unbiased values of producers and overall accuracy corrected by category proportions. The overall accuracy (P_o) when calculated by a simple tally of correct points was 91.3%, with a Tau coefficient (T_e) of 0.891 ± 0.051 (Table 2.6). The adjusted overall accuracy, corrected for bias using the map category proportions, was lower but well within acceptable limits at 81.9 (±8.4)% (Table 2.7).

User's accuracy was >95% for all major cover levels except for seagrass (67%). This was due to confusion with algal beds, a cover commonly intermixed with seagrass. Adjusted producers accuracy was >70% for all categories. Accuracy of mapped coral cover will be discussed in the section Percent Coral Cover.

Detailed Biological Cover

Error matrices for detailed biological cover are displayed in Table 2.8 for the simple tally of assessment points and 2.9 for the unbiased values of producers and overall accuracy corrected by category proportions. The overall accuracy (P_o) when calculated by a simple tally of correct points was 73.8%, with a Tau coefficient (T_e) of 0.711 ± 0.070 (Table 2.8). The adjusted overall accuracy, corrected for bias using the map category proportions, was lower at 61.0 (±9.8)% (Table 9). This was primarily due to the confusion between seagrass and algae, primarily NW of Vieques, which covers a very large proportion of the total mapped area.

Percent Hardbottom

Error matrices for percent hardbottom are displayed in Table 2.10 for the simple tally of assessment points and 2.11 for the unbiased values of producers and overall accuracy corrected by category proportions. The overall accuracy (P_o) when calculated by a simple tally of correct points was 83.2%, with a Tau coefficient (T_e) of 0.799 ± 0.065 (Table 2.10). The adjusted overall accuracy, corrected for bias using the map category proportions, was 86.1 (±4.5)% (Table 2.11). Greatest sources of error were between adjacent categories (e.g., site mapped as 70-90% hardbottom was actually 90-100%).

Table 2.8. Error matrix for detailed biological cover.

Accuracy Assessment (i)

Map data (j)	Algae 10% - <50%	Algae 50% - <90%	Algae 90% - 100%	Live Coral 50% - <90%	Mangrove 10% - <50%	Mangrove 50% - <90%	Mangrove 90% - 100%	Seagrass 10% - <50%	Seagrass 50% - <90%	Seagrass 90% - 100%	No Cover 90% - 100%	$n_{\cdot j}$	User's Accuracy (%)
Algae 10% - <50%	**7**	1										8	**87.5%**
Algae 50% - <90%	4	**23**	9	1				1			1	39	**59.0%**
Algae 90% - 100%		12	**64**	1					2			79	**81.0%**
Live Coral 50% - <90%				**0**								0	**n/a**
Mangrove 10% - <50%					**1**							1	**100.0%**
Mangrove 50% - <90%						**1**						1	**100.0%**
Mangrove 90% - 100%							**8**					8	**100.0%**
Seagrass 10% - <50%	1		1					**1**		1		4	**25.0%**
Seagrass 50% - <90%		3	2						**10**	5		20	**50.0%**
Seagrass 90% - 100%			3							**3**		6	**50.0%**
No Cover 90% - 100%											**17**	17	**100.0%**
$n_{i\cdot}$	12	39	79	2	1	1	8	2	12	9	18	n=183	
Producer's Accuracy (%)	**58.3%**	**59.0%**	**81.0%**	**0.0%**	**100.0%**	**100.0%**	**100.0%**	**50.0%**	**83.3%**	**33.3%**	**94.4%**	P_o =	**73.8%**

T_e = 0.711±0.070

Table 2.9. Error matrix for detailed biological cover, using individual cell probabilities. The overall accuracy and producer's accuracy were corrected for bias using the category proportions.

Accuracy Assessment (i)

Map data (j)	Algae 10% - <50%	Algae 50% - <90%	Algae 90% - 100%	Live Coral 50% - <90%	Mangrove 10% - <50%	Mangrove 50% - <90%	Mangrove 90% - 100%	Seagrass 10% - <50%	Seagrass 50% - <90%	Seagrass 90% - 100%	No Cover 90% - 100%	$\pi_{\cdot j}$	User's Accuracy (%)	User's CI (±%)
Algae 10% - <50%	**0.013**	0.002										0.015	**87.5%**	**23.4%**
Algae 50% - <90%	0.022	**0.129**	0.051	0.006				0.006			0.006	0.219	**59.0%**	**15.8%**
Algae 90% - 100%		0.031	**0.166**	0.003					0.005			0.205	**81.0%**	**8.8%**
Live Coral 50% - <90%												0.000	**n/a**	**n/a**
Mangrove 10% - <50%					**0.001**							0.001	**100.0%**	**0.0%**
Mangrove 50% - <90%						**0.003**						0.003	**100.0%**	**0.0%**
Mangrove 90% - 100%							**0.007**					0.007	**100.0%**	**0.0%**
Seagrass 10% - <50%	0.012		0.012					**0.012**		0.012		0.048	**25.0%**	**43.3%**
Seagrass 50% - <90%		0.043	0.029						**0.144**	0.072		0.289	**50.0%**	**22.4%**
Seagrass 90% - 100%			0.071							**0.071**		0.143	**50.0%**	**40.8%**
No Cover 90% - 100%											**0.071**	0.071	**0.0%**	**0.0%**
$p_{i\cdot}$	0.047	0.205	0.329	0.008	0.001	0.003	0.007	0.018	0.150	0.155	0.077	π=1		
Producer's Accuracy (%)	**27.2%**	**62.9%**	**50.5%**	**n/a**	**100.0%**	**100.0%**	**100.0%**	**68.0%**	**96.5%**	**45.9%**	**92.7%**	P_o =	**61.8%**	
Producer's CI (±%)	**11.6%**	**8.6%**	**4.1%**	**8.4%**	**n/a**	**n/a**	**0.0%**	**16.0%**	**14.8%**	**6.2%**	**13.0%**	Ci(±) =	**9.8%**	

Percent Coral Cover

The error matrix for percent coral cover is displayed in Table 2.12. The overall accuracy (P_o) was 77.8%, with a Tau coefficient (T_e) of 0.723 ± 0.075. As mentioned previously, a second matrix using the map category proportions could not be computed for percent coral cover.

Only two of the possible coral categories were present in the map (<10% and 10%-<50%), while two points in the accuracy assessment data were classified as 50%-<90%. Accuracy was very high for the softbottom habitats, where a low amount of coral is expected. There was lower accuracy for percent coral on hardbottom habitats. The decision between <10% and 10% - <50% was often difficult to determine, especially where there was a mix of octocorals and scleractinians. Additional ground truthing would improve accuracy of this category.

Conclusions

The results indicate that all levels of map data for Vieques have acceptable accuracy percentages and are suitable for a wide range of scientific and management applications (e.g., Kendall and Eschelbach 2006). Classification errors were primarily between similar habitats such as *Sand* and *Sand with Scattered Coral and Rock* which often lack clear separation when adjacent to each other; *Seagrass* and *Algae* which often occur in mixed beds; and between adjacent categories of percent hardbottom and coral cover. Although the classification schemes are not directly comparable due to region-specific categories, the level of accuracy for detailed structure was similar to that of other recent NOAA benthic habitat maps in St. John, US Virgin Islands (86%, [89% adjusted] Zitello et al. 2009), the Florida Keys

Table 2.10. Error matrix for percent hardbottom.

Map data (j) \ Accuracy Assessment (i)	0% - <10%	10% - <30%	30% - <50%	50% - <70%	70% - <90%	90% - 100%	$n_{\cdot j}$	User's Accuracy (%)
0% - <10%	**73**			1		2	76	**96.1%**
10% - <30%							0	**n/a**
30% - <50%		1	**1**				2	**50.0%**
50% - <70%							0	**n/a**
70% - <90%	2	1			**16**	10	29	**55.2%**
90% - 100%	1	1	1	3	8	**64**	78	**82.1%**
$n_{i\cdot}$	76	3	2	4	24	76	n=185	
Producer's Accuracy (%)	**96.1%**	**0.0%**	**50.0%**	**0.0%**	**66.7%**	**84.2%**	**P_o =**	**83.2%**
							T_e =	**0.799±0.065**

Table 2.11. Error matrix for percent hardbottom, using individual cell probabilities. The overall accuracy and producer's accuracy were corrected for bias using the category proportions.

Map data (j) \ Accuracy Assessment (i)	0% - <10%	10% - <30%	30% - <50%	50% - <70%	70% - <90%	90% - 100%	$\pi_{\cdot j}$	User's Accuracy (%)	User's CI (±%)
0% - <10%	**0.640**			0.009		0.018	0.666	**96.1%**	**4.5%**
10% - <30%							0.002	**n/a**	**n/a**
30% - <50%		0.002	**0.002**				0.003	**50.0%**	**70.7%**
50% - <70%							0.007	**n/a**	**n/a**
70% - <90%	0.012	0.006			**0.093**	0.058	0.168	**55.2%**	**18.5%**
90% - 100%	0.002	0.002	0.002	0.006	0.016	**0.127**	0.154	**82.1%**	**8.7%**
$p_{i\cdot}$	0.654	0.009	0.004	0.015	0.108	0.202	π=1		
Producer's Accuracy (%)	**97.9%**	**n/a**	**44.0%**	**n/a**	**85.4%**	**62.7%**	**P_o =**	**86.1%**	
Producer's CI (±%)	**2.4%**	**n/a**	**60.1%**	**n/a**	**9.3%**	**12.2%**	**CI(±) =**	**4.5%**	

Table 2.12. Error matrix for percent coral cover.

Map data (j) \ Accuracy Assessment (i)	Softbottom, Coral <10%	Softbottom, Coral 10% - <50%	Hardbottom, Coral <10%	Hardbottom, Coral 10% - <50%	Hardbottom, Coral 50% - <90%	$n_{\cdot j}$	User's Accuracy (%)
Softbottom, Coral <10%	**71**	2	2	1		76	**93.4%**
Softbottom, Coral 10% - <50%						0	**n/a**
Hardbottom, Coral <10%	2	1	**53**	10		66	**80.3%**
Hardbottom, Coral 10% - <50%			21	**20**	2	43	**46.5%**
Hardbottom, Coral 50% - <90%						0	n/a
$n_{i\cdot}$	73	3	76	31	2	n=185	
Producer's Accuracy (%)	**97.3%**	**0.0%**	**69.7%**	**64.5%**	**0.0%**	**P_o =**	**77.8%**
						T_e =	**0.723±0.075**

(86% [92% adjusted], Walker and Foster 2009), Palau (90%, Battista et al. 2007b), and the Main Hawaiian Islands (90%, Battista et al. 2007a). Comparisons with other accuracy assessments at the biological cover level are not possible due to the differences in the classification scheme.

For additional details on accuracy assessment methods and computational details see the references in the literature cited section.

2.5 SUMMARY STATISTICS

Of the area considered during the mapping process, 127.4 km² was designated as *Land*. The remaining 357.6 km² were described by 3229 polygons corresponding to the structure and biological cover types of the habitat classification scheme outlined in Section 2.2.

Of these 357.6 km^2, *Unconsolidated Sediment* and *Coral Reef and Hardbottom* each accounted for 238 km^2 and 119.6 km^2, respectively, of Major Structure type (Table 2.13). Together, *Unconsolidated Sediment* and *Coral Reef and Hardbottom* account for 99.99% of Major Structure type; the remaining 0.01% corresponds to *Artificial* structures. The 0.05 km^2 of *Artificial* type is comprised primarily of Mosquito Pier on the north shore, piers in Esperanza on the south shore, and the sunken U.S.S Killen in Bahia Salina del Sur.

Summary statistics for Detailed Structure highlight the composition of Major Structure types (Table 2.13). Note that Detailed Structure percentages are derived from total mapped area, not within the corresponding Major Structure classification. *Sand* is the most common Detailed Structure type, accounting for 61.6% of the total mapped area (Table 2.13). *Mud* and *Sand with Scattered Coral and Rock* are considerably less common *Unconsolidated Sediment* types, accounting for 2.2% and 2.7% respectively. At 11% of total area, *Pavement* is the second most dominant structure type overall and the

Table 2.13. Area summary of major and detailed geomorphological structure classes in the Vieques benthic habitat map.

MAJOR STRUCTURE	AREA (km^2)	PERCENT AREA	DETAILED STRUCTURE	AREA (km^2)	PERCENT AREA
Coral Reef and Hardbottom	119.56	33.44	Rock/Boulder	1.38	0.39
			Aggregate Reef	13.79	3.86
			Individual Patch Reef	6.46	1.81
			Aggregated Patch Reef	1.91	0.54
			Spur and Groove	0.02	0.01
			Pavement	39.37	11.01
			Pavement with Sand Channels	5.98	1.67
			Reef Rubble	17.53	4.90
			Rhodoliths	33.11	9.26
Unconsolidated Sediment	237.95	66.55	Sand	220.39	61.64
			Mud	7.88	2.20
			Sand with Scattered Coral and Rock	9.69	2.71
Other Delineations (Land excluded)	0.05	0.01	Artificial	0.05	0.01
Total	357.56	100.00		357.56	100.00

Table 2.14. Area summary of major and detailed cover classes in the Vieques benthic habitat map (excludes land and non-classified artificial areas).

MAJOR COVER	AREA (km^2)	PERCENT AREA	PERCENT COVER	AREA (km^2)	PERCENT AREA
Algae	156.91	43.88	10% - <50%	5.24	1.47
			50% - <90%	78.96	22.08
			90% - 100%	72.71	20.34
Seagrass	171.28	47.90	10% - <50%	16.92	4.73
			50% - <90%	102.29	28.61
			90% - 100%	52.08	14.56
Live Coral	0	0	10% - <50%	0	0
			50% - <90%	0	0
			90% - 100%	0	0
Mangrove	3.81	1.07	10% - <50%	0.42	0.12
			50% - <90%	0.93	0.26
			90% - 100%	2.46	0.69
No Cover	25.55	7.15	90% - 100%	25.55	7.15
Total	357.56	100.00		357.56	100.00

predominant detailed structure type within *Coral Reef and Hardbottom*. Other common structure types are *Rhodoliths*, which account for 9.3% of total area, and *Aggregate Reef*, which contributes to 3.4% of total area. Although ecologically significant, patch reefs, in the form of *Individual Patch Reefs* and *Aggregated Patch Reefs*, only comprise just over 2% of all the nearshore habitat of Vieques.

Table 2.15. Area summary of percent coral cover for Vieques habitats.

PERCENT CORAL COVER	AREA (km^2)	PERCENT AREA
<10%	333.65	93.31
10% - <50%	23.91	6.69
50% - <90%	0	0
90% - 100%	0	0
N/A	0.004	0.001
Total	357.56	100.00

Seagrass and *Algae* were the dominant biological cover types, accounting for 47.9% and 43.9% of the mapped area, respectively (Table 2.14). *Seagrass* was most common, however it should be noted that beds of submerged vegetation are often a mix of seagrass and algae, and as noted in the previous section, distinguishing between the two in aerial imagery can be difficult. Nearly half of the 43.9 km^2 of algal dominance is covered by a continuous distribution (90% - 100%). This is in large part due to the inclusion of turf algae as a mapped species, since much of Vieques hardbottom is covered by turf in the absence of live coral. Areas with *No Cover* account for 7.2% of the total area. *Mangrove*, a less common dominant cover, constitutes 1.1% of the study area. Although live coral colonies exist throughout the Vieques seascape, no area was mapped that was dominated by *Live Coral*.

Only 23.9 km^2 exhibited a Percent Coral Cover of 10% to <50%. These areas account for 6.7% of the study area, while 93.3%, or 333.7 km^2, have less than 10% coral cover. Furthermore, Coral Cover does not exceed 50% within any single minimum mapping unit of the study area. For this, it is important to remember the influence of minimum mapping units in the habitat mapping process. It is possible that some areas of Vieques are comprised of greater than 50% coral cover, but these areas were not large enough to be mapped with a contiguous minimum mapping unit of 1000 m^2.

The composition and extent of geomorphological structure and biological cover around Vieques varies over space (Figures 2.36-2.38; Kendall and Eschelbach 2006). The area north-northwest of Vieques is dominated by sand with submerged aquatic vegetation, interspersed by numerous patch reefs. Moving east from Isabel Segunda, a system of shallow *Lagoons* and *Reef Flats* extend from shore, bordered seaward by a line of *Pavement* and *Aggregate Reef*. A large area of *Rhodoliths* dominated by algae cover sits offshore in the deeper water. The formation of *Pavement* and *Aggregate Reef* extends around the eastern tip of the island to the south side, where it is more extensive than on the north. Two linear systems of *Pavement* and *Aggregate Reef* are present on the south coast; one close to shore, while another is further offshore along the shelf edge. The large area lying between these two reef systems southeast of Vieques is a depression approaching 30 m in depth that was primarily mapped as *Reef Rubble*. Available ground-truth and accuracy assessment data indicated that the structure constitutes a mix of rubble, pavement and sand. However, the heterogeneity of the structure and depth of this area made distinguishing between the different signatures difficult.

Area designated as *Unknown* exceeds the depth limits (~30 m) for mapping with aerial imagery. NOAA's Biogeography Branch is undertaking a similar effort to develop habitat maps of the deep-shelf area south of Vieques, including the El Seco area to the east. The maps will be derived from acoustic data collected with a multibeam echosounder (MBES).

2.6 COMPARISON TO PREVIOUS NOAA HABITAT MAPS OF VIEQUES

The 2009 mapping effort described in this report marks the second such effort NOAA has conducted to map shallow water marine benthic habitats of Vieques. Components of the new mapping product that mark an improvement over Kendall et al. (2001) include an expanded habitat classification scheme, smaller minimum mapping units, more recent imagery, and improved positional accuracy (Table 2.16). In addition, within the extent area used for this mapping effort, a larger total area was mapped than in the previous mapping effort (~81 km^2). For example, some areas that were mapped as unknown in the previous effort were able to be delineated in the new map due to better remote sensing imagery. These include areas that had been obscured by clouds in the 1999 imagery (e.g., outside the mouth of Puerto Ferro, and southeastern Ensenada Honda) and where image clarity was poor (e.g., the vast rhodolith/algae field northeast of the island).

NOAA's revised approach to mapping nearshore ecosystems has provided significant advantages to better represent the natural environment. As displayed in Table 2.16, the 2009 map was created with finer scale

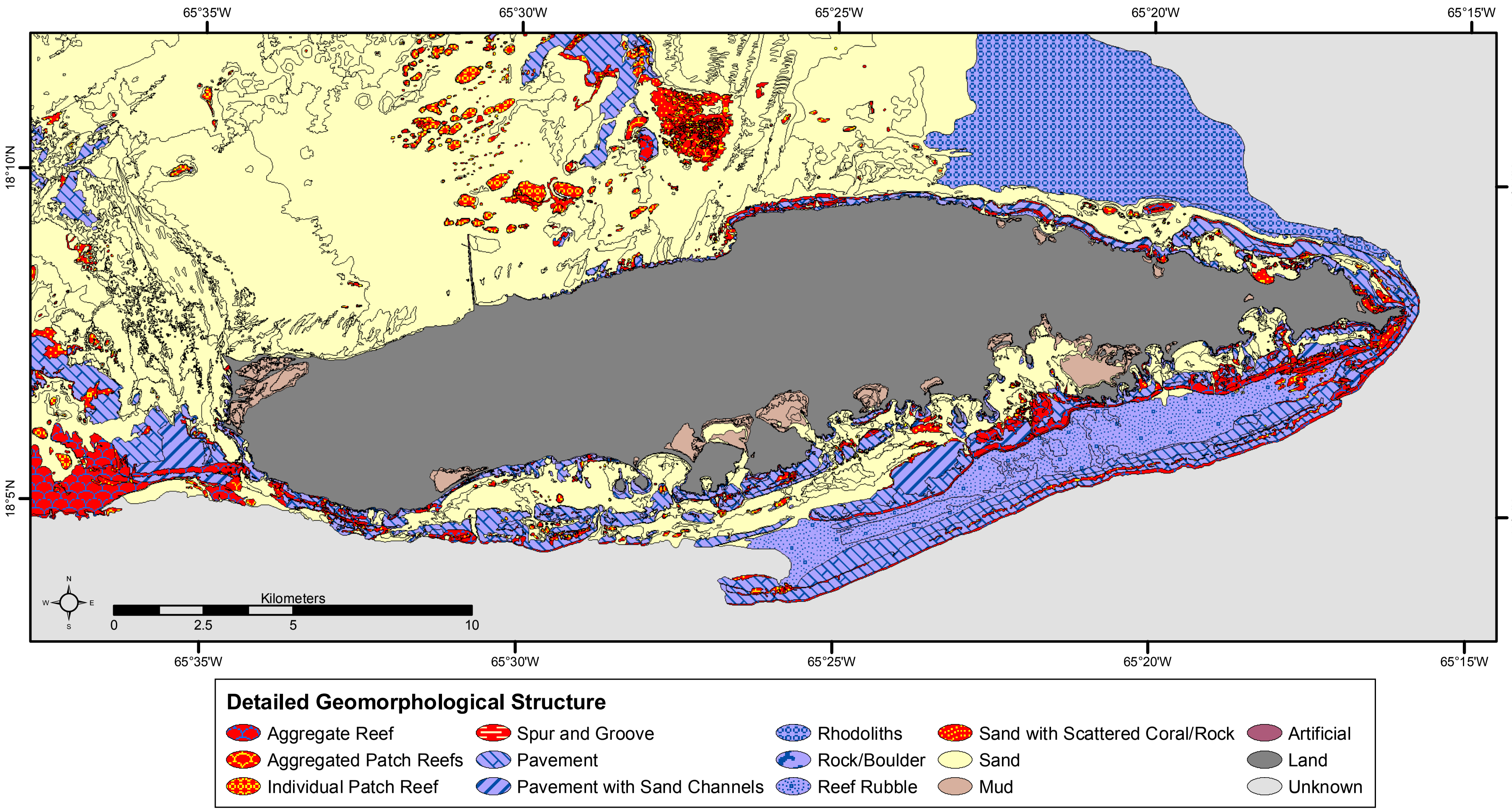


Figure 2.36. Detailed geomorphological structure.

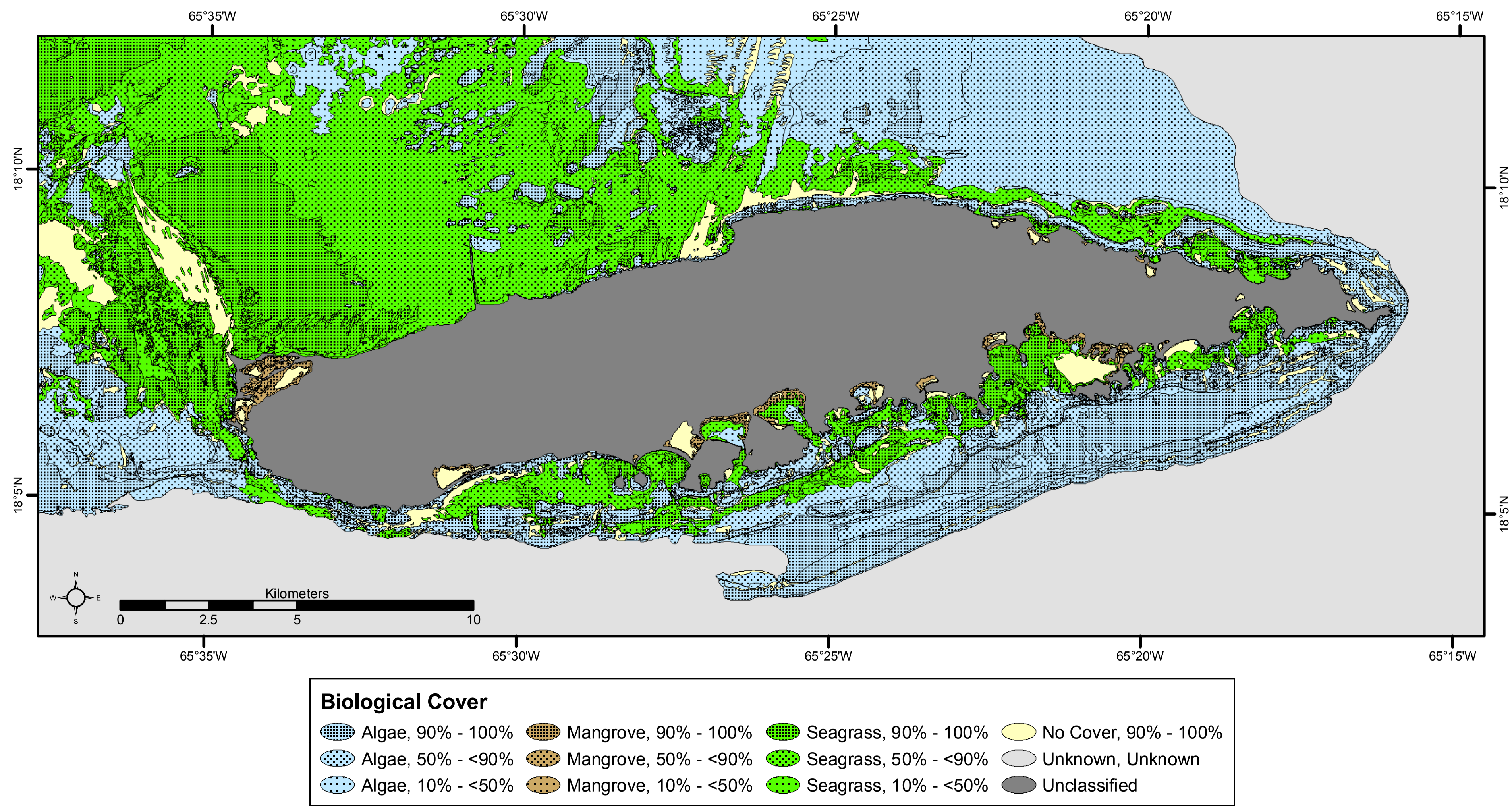


Figure 2.37. Dominant biological cover.

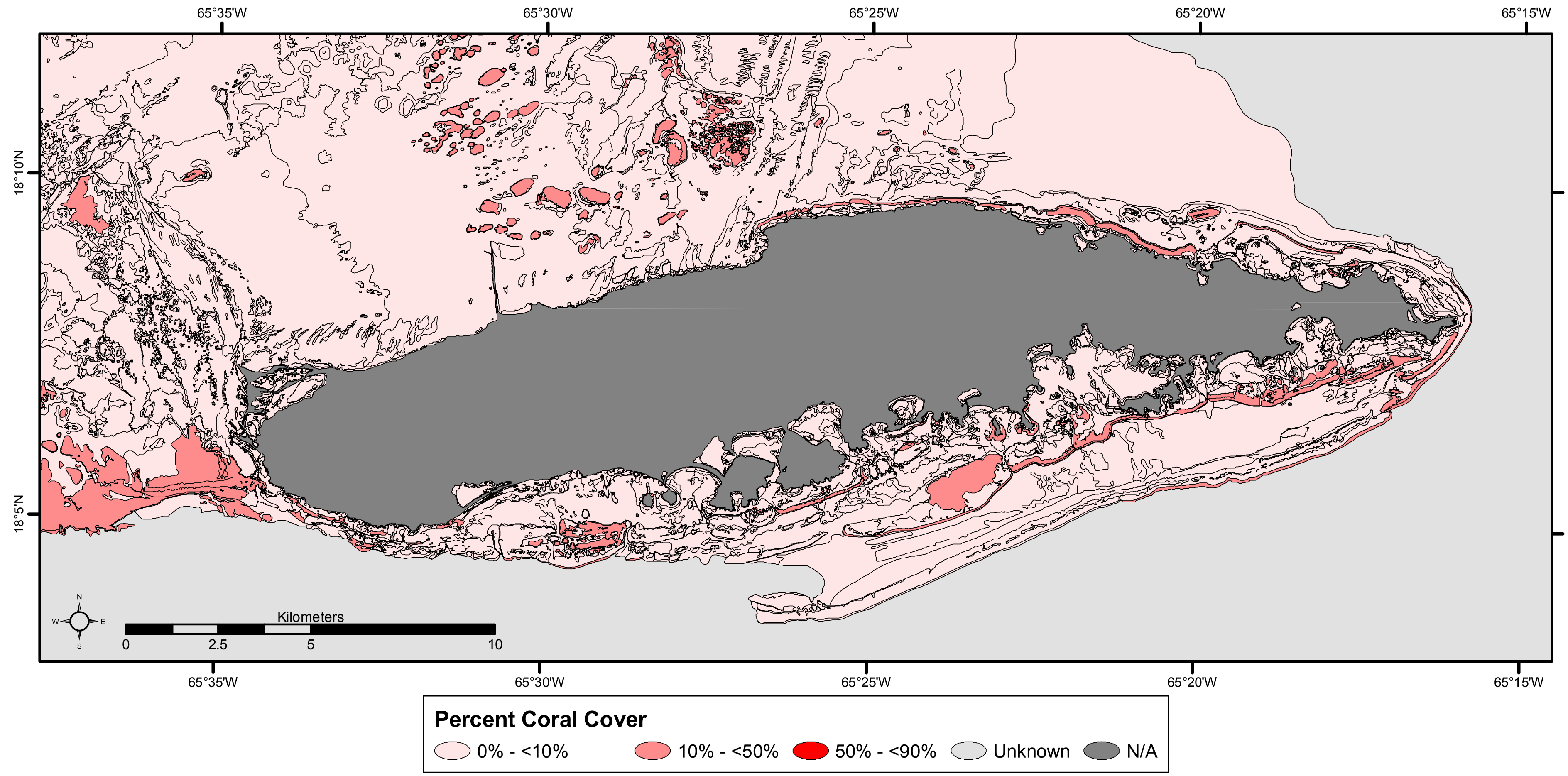


Figure 2.38. Percent coral cover.

mapping standards in both scale of delineation and minimum mapping unit. Following pan-sharpening, the pixel resolution of the IKONOS imagery was 1 m, while the pixel resolution of the 2007 Army Corps orthophotography was 0.3 m. In contrast, the source imagery of the 2001 maps was 2.4 m. The finer scale imagery and reduced scale of delineation resulted in enhanced line accuracy and detail.

Table 2.16. Comparison of basic map characteristics between a previous NOAA effort (2001) and current map of Vieques (2009). Excludes land and unknown areas.

		NOAA MAPPING EFFORT	
		2001	**2009**
MAP	Source Imagery Date	1999	2006-2008
	Scale of Delineation	1:6000	1:4000
	Minimum Mapping Unit (m^2)	4,046	1,000
FEATURE	Number of Polygons	882	3229
	Mean Polygon Area (m^2)	313,930	110,735
	Total Mapped Area (km^2)	276.57	357.56
	Sum of Polygon Edges (km)	2983	5544
	Mean Polygon Length (km)	3.39	1.72

A four-fold reduction in the MMU from an acre (4,046 m^2) to 1000 m^2 in the 2009 mapping effort had a large impact on the final content of the mapping product. The smaller minimum mapping unit results in ~3.5 times as many polygons and about three times as small mean polygon area. The reduced MMU allowed for a more accurate depiction of patchy environments. For example, in the previous mapping effort, most of the patch reefs north of the island were below the MMU and thus grouped together into polygons of aggregated patch reefs. As illustrated by Figure 2.39, many of these patch reefs could often be individually drawn in the new map. In total, 609 individual patch reefs were mapped in the 2009 map, compared to 88 within the same extent in 2001. Although other factors may have contributed to this difference (e.g., image quality), the ability to delineate more features due to the reduced scale and MMU is likely the primary reason.

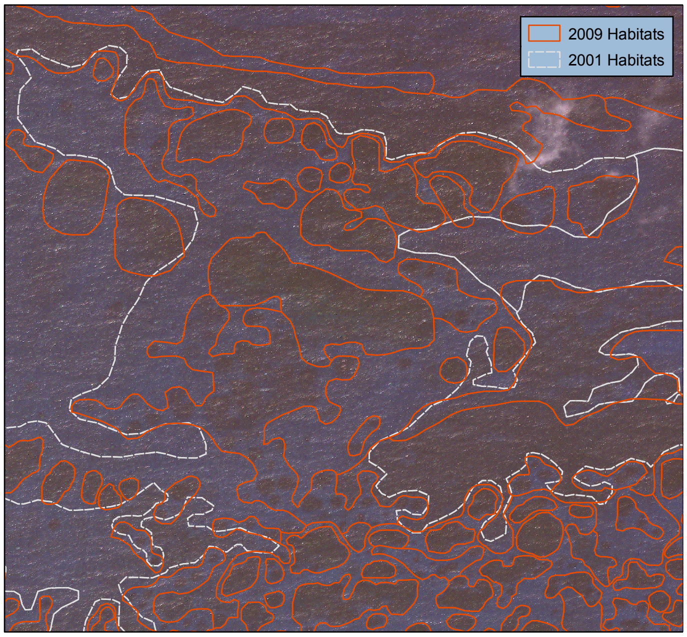


Figure 2.39. Comparison of 2001 and 2009 NOAA benthic habitat boundaries to illustrate the difference in the minimum mapping unit on delineation of patch reefs north of Vieques.

Periodic re-mapping of an area can serve as an important monitoring tool. Although the different classification schemes and MMUs prohibit a quantitative comparison between the 2001 and 2009 maps, there appear to be some changes in biological cover on softbottom between the two time periods. The Escollo de Arenas, extending from the northwest tip of the island, is a dynamic feature whose shape and shifting sands are influenced by longshore and tidal currents (Rodriguez and Trias 1989). Large storm events can transport large volumes of sediment into adjacent seagrass beds (e.g., Hurricane Hugo, Rodriguez et al. 1994). Areas south/west of the sand wedge have experienced a regrowth of seagrass between 1999 and 2007, when the previous and newer imagery was taken, respectively (Figure 2.40). In addition, the eastern edge of Escollo de Arenas has been filled in by vegetation. One of the new satellite images captured the strong currents and sediment transport that can occur in this area (Figure 2.40). The high turbidity in the water column obscured the bottom on much of the north side of the island on this day. Tidal inflow of a sediment plume into Laguna Kiani, a mangrove lagoon on the northwest tip, was also visible. Further seagrass re-growth is apparent along the southeast coast of Vieques, including Bahia Salina del Sur.

2.7 PROJECT DELIVERABLES

A suite of products associated with the Vieques benthic habitat map are available to the public on a NOAA Biogeography Branch website devoted to this mapping effort (http://ccma.nos.noaa.gov/ecosystems/coralreef/vieques.html). The project deliverables include:

• Benthic habitat maps in GIS format,

• Remotely sensed imagery, including satellite and airborne imagery,

Figure 2.40. Comparison of seagrass coverage near the Escollo de Arenas in the 1999 (left) and 2007 (middle) imagery. Example areas of seagrass growth east and west of the sand wedge are labeled 1 and 2. Another recent IKONOS image (right panel) was captured on a day of strong currents and high turbidity (labels 3 and 4).

• Underwater video of ground validation and accuracy assessment field sites, including GIS files of their locations,

• Classification manual (contained in this report),

• Description of the specific methods used to create the habitat maps (contained in this report),

• Assessment of the thematic accuracy of the maps (contained in this report),

• FGDC-compliant metadata for all GIS products, and

• An interactive, web-based map that allows users to query and display all spatial datasets and underwater video.

ACKNOWLEDGEMENTS

Many thanks to Captain Angel Nazario (*Aquanauta*) and his assistant Joel (Joiito) Rivera for getting us safely to/from our sites and for their assistance in the field. Zach Hecht-Levitt and Peter Mueller assisted in the processing of video data. Thanks to Ken Buja for his patience in fielding questions about the Habitat Digitizer and for designing the Vieques BIOMapper. Thanks to John Burke (NOAA/CCFHR) and Sam Purkis (National Coral Reef Institute) for sharing supplemental ground validation data. Funding for this work was provided by NOAA's Office of Response and Restoration.

LITERATURE CITED

Battista, T.A., B.M. Costa and S.M. Anderson. 2007a. Shallow-water benthic habitats of the Main Eight Hawaiian Islands (DVD). NOAA Technical Memorandum NOS NCCOS 61, Biogeography Branch. Silver Spring, MD.

Battista, T.A., B.M. Costa and S.M. Anderson. 2007b. Shallow-water benthic habitats of the Republic of Palau. NOAA Technical Memorandum NOS NCCOS 59, Biogeography Branch. Silver Spring, MD.

Bauer, L.J., C. Menza, K.A. Foley, and M.S. Kendall. 2008. An ecological characterization of the marine resources of Vieques, Puerto Rico. Part I: Historical data synthesis. Prepared by National Centers for Coastal Ocean Science (NCCOS) Biogeography Branch in cooperation with the Office of Response and Restoration. Silver, Spring, MD. NOAA Technical Memorandum NOS NCCOS 86. 121 pp.

Buja, K. 2008a. (Online). Habitat digitizer extension for ArcGIS, version 5. NOAA Biogeography Branch. Silver Spring, MD. Available at: : http://ccma.nos.noaa.gov/products/biogeography/digitizer/welcome.html.

Buja, K. 2008b. (Online). Find adjacent features. ESRI Support Center. Available at: http://arcscripts.esri.com/details.asp?dbid=15805. Last accessed July 2009.

Buja, K. 2008c. (Online). Find overlapping polygons. ESRI Support Center. Available at: http://arcscripts.esri.com/details.asp?dbid=15198. Last accessed July 2009.

Card, D.H. 1982. Using known map categorical marginal frequencies to improve estimates of thematic map accuracy. Photogrammetric Engineering and Remote Sensing 48: 431-439.

Cohen, J. 1960. A coefficient of agreement for nominal scale. Educational and Psychological Measurement 20: 37-46.

Congalton, R.G. and K. Green. 1999. Assessing the Accuracy of Remotely Sensed Data: Principles and Practices. CRC/Lewis Press, Boca Raton, FL. 137 pp.

ESRI. 2008. ArcGIS 9.3. Redlands, CA: Environmental Systems Research Institute. Available: http://www.esri.com/.

Hay, A.M. 1979. Sampling designs to test land-use map accuracy. Photogrammetric Engineering and Remote Sensing 45: 529-533.

Hedley, J.D., A.R. Harborne and P.J. Mumby. 2005. Simple and robust removal of sun glint for mapping shallow-water benthos. International Journal of Remote Sensing 26(10): 2107 – 2112.

Kendall, M.S. and K.A. Eschelbach. 2006. Spatial analysis of the benthic habitats within the limited-use zones around Vieques, Puerto Rico. Bulletin of Marine Science 79(2): 389-400.

Kendall, M.S., C.R. Kruer, K.R. Buja, J.D. Christensen, M. Finkbeiner, R.A. Warner and M.E. Monaco. 2001. Methods used to map the benthic habitats of Puerto Rico and the U.S. Virgin Islands. NOAA Technical Memorandum NOS NCCOS CCMA 152. Silver Spring, MD. 45 pp.

Ma, Z. and R.L. Redmond. 1995. Tau coefficients for accuracy assessment of classification of remote sensing data. Photogrammetric Engineering and Remote Sensing 61: 435-439.

Rodriguez, R.W. and J.L. Trias. 1989. Maps showing characteristics of the Escollo de Arenas sand and gravel deposit, Vieques Island, Puerto Rico. Department of the Interior, U.S. Geological Survey. Map MF-2108.

Rodriguez, R.W, R.M.T. Webb and D.M. Bush. 1994. Another look at the impact of Hurricane Hugo on the shelf and coastal resources of Puerto Rico, USA. Journal of Coastal Research 10(2): 278-296.

Steel, G.D. and J.H. Torrie. 1960. Principles and Procedures of Statistics. McGraw-Hill Book Company, Inc., New York. 481 pp.

Story, M. and R. Congalton. 1986. Accuracy assessment: A user's perspective. Photogrammetric Engineering and Remote Sensing 52: 397-399.

Walker, B.K. and G. Foster. 2009. Final report: Accuracy assessment and monitoring for NOAA Florida Keys mapping: AA ROI-1 (near American Shoal). National Coral Reef Institute, Nova Southeastern University, Dania Beach, FL. 32 pp.

Wentworth, C.K. 1922. A scale of grade and class terms for clastic sediments. Journal of Geology 30(5): 377-392.

Zitello, A.G., L.J. Bauer, T.A. Battista, P.W. Mueller, M.S. Kendall and M.E. Monaco. 2009. Benthic habitats of St. John, U.S. Virgin Islands. NOAA Technical Memorandum NOS NCCOS 96. Silver Spring, MD.

CHAPTER 3: CHARACTERIZATION OF REEF AND HARDBOTTOM HABITATS, ASSOCIATED FISH COMMUNITIES, AND MARINE DEBRIS IN VIEQUES

Laurie J. Bauer[1,2,] and Matthew S. Kendall[1]*

[1]Center for Coastal Monitoring and Assessment, National Centers for Coastal Ocean Science, National Ocean Service, NOAA, 1305 East-West Hwy, Silver Spring, MD 20910

[2]Consolidated Safety Services, Inc., Fairfax, VA 22030, under NOAA Contract No. DG133C07NC0616

[*]Corresponding author: laurie.bauer@noaa.gov

3.1 INTRODUCTION

In Part I of the ecological characterization (Bauer et al. 2008), prior research and monitoring activities of the benthic habitats and fish communities of Vieques were summarized. An island-wide stratified random survey of benthic habitats and associated fish communities has never been conducted around Vieques. Such surveys are useful for management of marine resources and marine spatial planning, and can be used to inform future research and monitoring decisions.

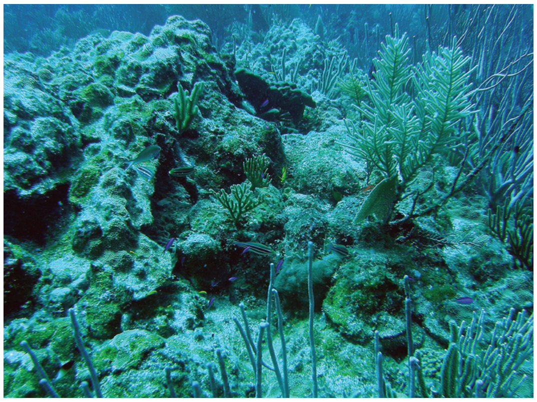


Image 3.1. Vieques coral reef.

The objectives of this section are to characterize fish assemblages, benthic communities, and marine debris on coral reef and other hardbottom habitats around Vieques using a comprehensive island-wide survey. These data will serve as a baseline to monitor future changes in benthic cover, population estimates and size spectra of fish over time. Although submerged aquatic vegetation and mangroves are also utilized by many fish species, efforts for the island-wide survey were concentrated on hardbottom habitats due to logistical limitations. Fish populations in several Vieques lagoons (Puerto Mosquito, Puerto Ferro, Ensenada Honda, Puerto Negro) and softbottom shelf areas were also surveyed and will be discussed in Chapter 4.

3.2 METHODS

Site Selection

Field surveys were conducted from May 14-26, 2007 to characterize the coral reefs, hardbottom habitats, and their associated fish communities around Vieques. Reef/hardbottom habitat out to 3 nm (5.6 km) offshore and shallower than 100 ft depth was designated as the survey area. An important issue identified by local interest groups was how the condition of reefs differs in regions that have experienced varying degrees of human activity. Another important consideration in survey design was to partition sites on both the north and south sides of the island, which have inherent differences in shelf morphology, currents, and bathymetry. Based on these two factors, ten strata were defined (Figure 3.1, Table 3.1). The five former land use zones were identified, from west to east, as the 1: Naval Ammunition Support Detachment (NASD, also known as the Naval Ammunition Facility), 2: the Civilian Area (CA), 3: the Eastern Maneuver Area (EMA) and the Secondary Impact Area (SIA), 4: the Live Impact Area (LIA), and 5: the Eastern Conservation Area (ECA). Each zone was further subdivided into north and south regions. Hereafter, the strata will be referred to as 1-5 heading west to east, followed by north/south (e.g., 1-North).

Table 3.1. Allocation of survey sites by strata.

Stratum	Former Land Use Zone	Number of Survey Sites		
		North	South	Total
1	Naval Ammunition and Support Detachment (NASD)	6	10	16
2	Civilian Area (CA)	8	9	17
3	Eastern Maneuver Area (EMA) / Secondary Impact Area (SIA)	6	11	17
4	Live Impact Area (LIA)	6	8	14
5	Eastern Conservation Area (ECA)	5	6	11
	Total	31	44	75

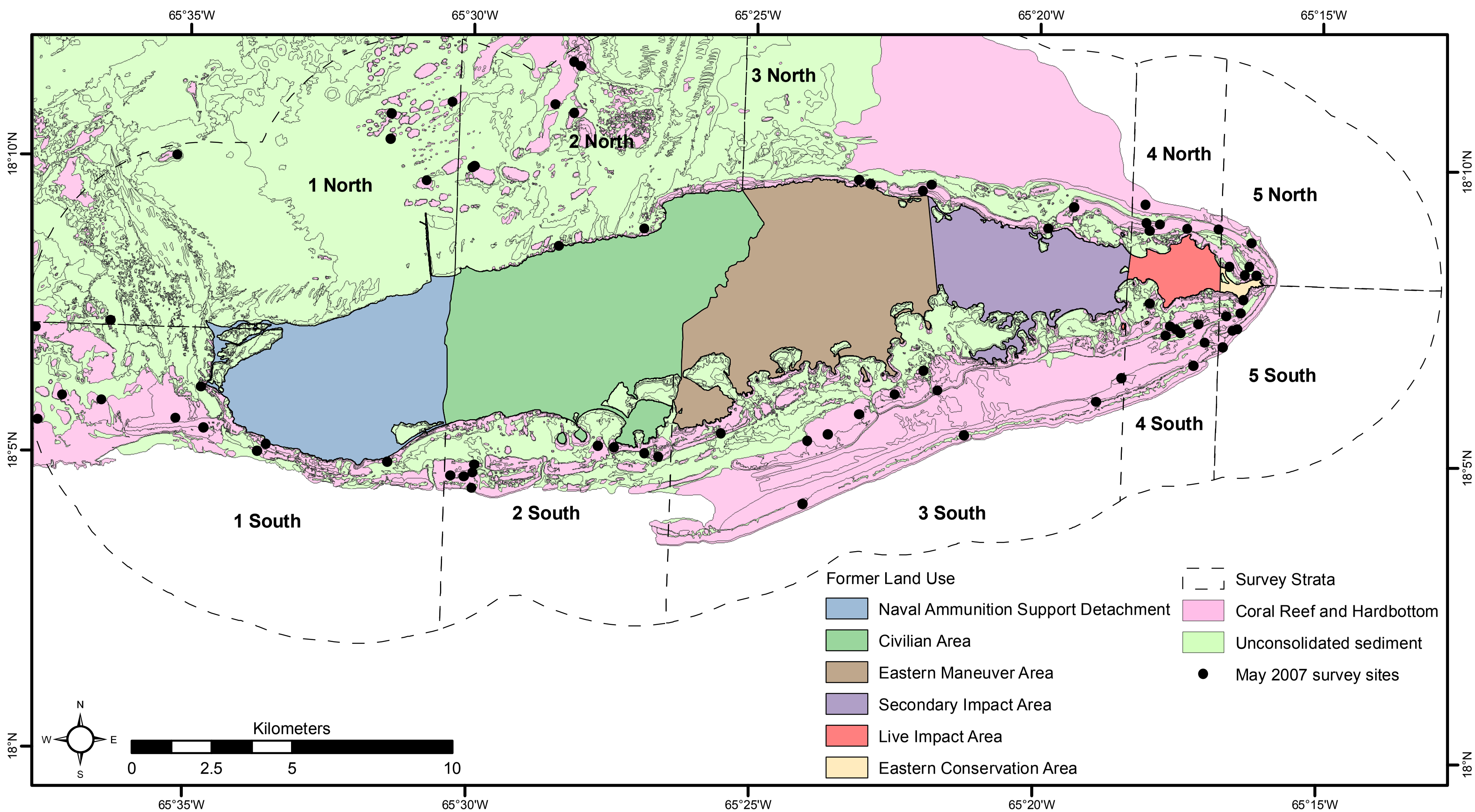


Figure 3.1. Former land use, survey strata and site locations of the May 2007 survey of hardbottom benthic habitats, fish communities, and marine debris.

A total of 75 sites were surveyed. The number of total sites was pre-determined by the time allotment for the survey and an estimate of the number of sites that could be completed each day. A minimum of five sites was included in each stratum to ensure an adequate minimum number of surveys for statistical comparisons. Remaining survey effort was then divided among strata based on proportional area of reef and hardbottom within an individual stratum in relation to the total amount of reef/hardbottom in the survey area (Table 3.1). As the new benthic habitat map (Chapter 2) was not complete at the time of the survey, the amount of reef/hardbottom in a previous benthic habitat map of Vieques (Kendall et al. 2001) was used as the basis for site selection purposes. Sites were randomly selected within the ten strata in ArcGIS using Hawth's Spatial Analysis Tools v.3.27 (Beyer 2004) (Figure 3.1).

Table 3.2. Distribution of survey sites by detailed hardbottom habitat structure. See Chapter 2 for classification scheme.

Detailed Structure Type	Number of Survey Sites	Percent of Sites
Aggregate Reef	19	25.3
Individual Patch Reef	11	14.7
Aggregated Patch Reefs	2	2.7
Pavement	29	38.7
Pavement w/ Sand Channels	6	8.0
Rhodoliths	1	1.3
Sand w/ Scat. Coral/Rock	7	9.3
Total	75	100.0

In Chapter 2, reef and hardbottom was categorized into detailed geomorphological structure types in the new benthic habitat map. The number of sites surveyed relative to detailed geomorphological structure type, based on the new map are displayed in Table 3.2. The majority of sites were located in hardbottom types that account for the highest coverage by area (e.g., pavement, aggregate reef). In contrast, a relatively small percentage of sites were surveyed in aggregated patch reefs, which represents a relatively small proportion of the hardbottom types around Vieques by area. Although the new benthic habitat classification scheme (Chapter 2) now includes sand w/ scattered coral and rock as a softbottom structure type, this was previously designated as coral reef and hardbottom and was hence included in the survey area. Only one site was surveyed in the rhodolith class; although this structure type encompasses a large area (Chapter 2), most of this area had been unclassified in the previous map and not considered in site allocation.

Field Methods

The survey of benthic features, fish communities and marine debris were all conducted within a 25 x 4 m transect (100 m^2), along a random compass heading. Two divers performed the survey at each site. One diver was responsible for visual counts and size estimation of fish species. The second diver quantified benthic features and marine debris.

Benthic Habitat Composition

The habitat diver assigned an overall bottom type (i.e., hard or soft bottom) to each transect based on *in situ* observation. Data on the percent cover of abiotic and biotic composition at each survey site were recorded within five 1 m^2 quadrats placed randomly along the 25 x 4 m transect. The quadrat was placed at each randomly chosen distance and systematically alternated from one side to the other side along the transect tape (Figure 3.2). Several variables were measured to characterize benthic composition and structure (Table 3.3). The quadrat was divided into 100 smaller 10 x 10 cm squares (1 small square = 1% cover) to help the diver with estimation of percent cover. Percent cover was determined by looking at the quadrat from above and visually estimating percent cover in a two dimensional plane. The information recorded included:

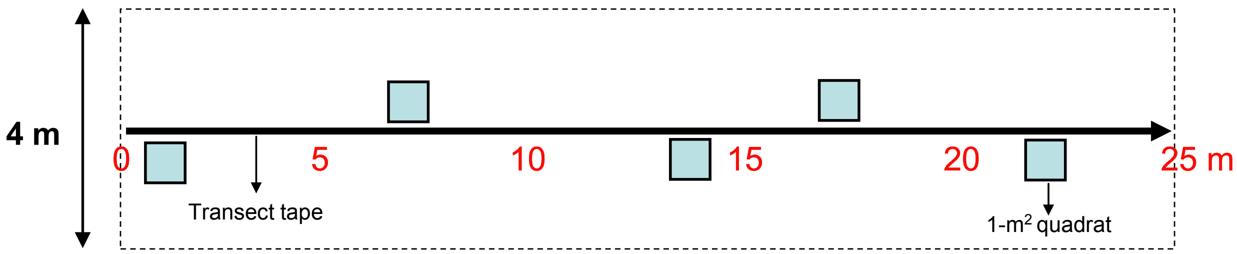


Figure 3.2. Schematic representation of the placement of the 1 m^2 quadrat along a 25 m transect tape during fish and benthic substrate surveys. Broken line represents total survey area (100m^2).

Abiotic cover - the percent cover (to the nearest 1%) of four abiotic substrate categories (hardbottom, sand, rubble, fine sediments/silt) was estimated within each 1 m^2 quadrat. The maximum height of the hardbottom was also measured.

Biotic cover - the percent cover (to the nearest 0.1%) of algae, seagrass, live corals, sponges, gorgonians, and other biota was estimated within each 1 m^2 quadrat. Taxa were identified to the following levels: stony coral-species, algae-morphological group, sponge-morphological group, and gorgonians-morphological group. Species identified as *Montastrea annularis* refer to the *M. annularis* complex. For stony and fire corals, the percentage of bleached coral and diseased/dead coral was estimated to the nearest 0.1 percent.

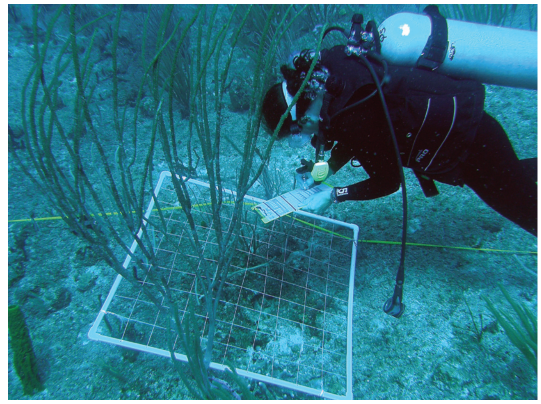


Image 3.2. Diver quantifying habitat composition.

Maximum canopy height - the maximum canopy height of sponges, gorgonians, and soft algal groups was recorded to the nearest 1 cm in each quadrat.

Number of individuals - the number of individual upright sponges, gorgonians, non-encrusting anemones, and non-encrusting hydroids was recorded in each quadrat.

Rugosity - rugosity was measured by placing a 6 m chain at two randomly selected and non-overlapping positions, ensuring no overlap, along the 25 m belt transect. The chain was positioned along the centerline of the transect such that it followed the substrate's relief, and the straight-line horizontal distance covered by the chain was measured.

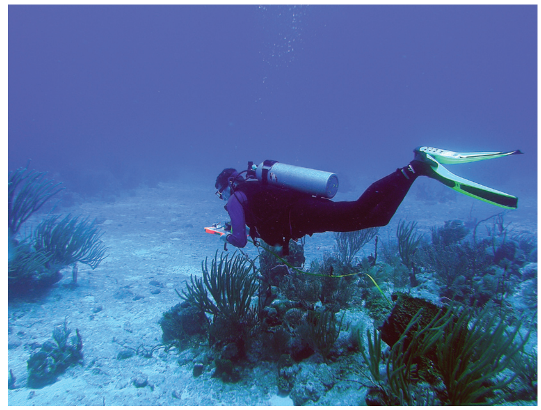


Image 3.3. Diver conducting fish survey.

The habitat diver also counted the abundance of spiny lobsters (*Panulirus argus*), long-spined urchins (*Diadema antillarium*), and the abundance/maturity of queen conchs (*Strombus gigas*) within the 25 x 4 m transect at each site.

Fish Census

Fish surveys were conducted along the 25x4 m transect (100 m^2) using a fixed survey duration of 15 minutes regardless of habitat type or complexity. The number of individuals per species was recorded in 5 cm size class increments up to 35 cm using visual estimation of fork length. Individuals greater than 35 cm were recorded as an estimate of the actual fork length to the nearest centimeter. Fish were identified to the lowest possible taxonomic unit.

Marine Debris

The number and type of marine debris within the 100 m^2 transect were recorded. The size of marine debris and the area of affected habitat were estimated. The degree of colonization and any injuries to benthic organisms were also noted. Special attention was paid to the presence of unexploded ordnance. For safety reasons, a Navy UXO (unexploded ordnance) safety contractor diver accompanied divers at all dive sites where munitions could potentially be present. In addition to recording any debris, including ordnance, within the survey area, ordnance observed outside the 100 m^2 transect was also described, photographed, and documented for U.S. Navy records.

Data Analysis

Benthic Habitat

The five quadrat measurements within each transect were averaged and cumulative coral species richness was calculated for each survey location. Average site values were used to calculate means and standard er-

rors of measured variables for the entire study area, by strata, and by detailed geomorphological structure type using the sampling weights for the study area (SAS v9.1, Proc SurveyMeans). Potential differences in metrics among strata were investigated using parametric ANOVA for normally distributed data (e.g., coral species richness) and non-parametric Wilcoxon tests for non-normally distributed data (e.g., percent cover of major cover groups). When the overall test was significant, pairwise comparison's were made using Tukey's HSD (Honestly Significant Difference) or the corresponding non-parametric Dunn's test (Zar 1999). Data were plotted in ArcGIS (v9.3, ESRI) to examine broad spatial patterns in the benthic cover variables.

Fish Assemblages

A summary of all species observed in this characterization was created. Domain-wide estimates were computed employing methods described by Cochran (1977) for a stratified sampling design using the data, strata and corresponding sampling weights. Percent occurrence, mean density and biomass (per $100m^2$) and corresponding standard errors (SE) were calculated for each species. Mean density and biomass were also calculated for each family and trophic group for the overall survey area. Trophic groups include piscivores, herbivores, invertivores, and zooplanktivores and were defined for each species based on diet information from Randall (1967). However, it is important to note that the diet of many species is composed of a mix of these groups; generally when a species' diet consisted of more than one trophic group, the group that comprised the higher percentage of the diet was chosen. Biomass was calculated using published length-weight relationships using the formula,

$$W = \alpha L^{\beta}$$

where L is length in centimeters and W is weight in grams. The midpoint of each size class was used for L values, or actual length was used for fish >35 cm (for fish 0-5 cm in length, 3 cm was used as we don't typically observe fish <1 cm). Values for the α and β coefficients were obtained from FishBase (Froese and Pauly, 2008). Biomass for species with no published length-weight relationships was calculated using terms for the closest congener with most similar morphology.

Species diversity was calculated using the Shannon Index (H'), a measure that incorporates both richness and evenness:

$$H' = \Sigma_i p_i(\log_e p_i)$$

Total fish density, biomass, richness, and diversity were compared among strata. Parametric Analysis of Variance (ANOVA) was used when assumptions of normality and homogeneity of variance were met (i.e., richness and Shannon diversity); and non-parametric Wilcoxon tests when assumptions were not met (i.e., total abundance and total biomass). When the overall test was significant, pairwise comparisons were made using Tukey's HSD (Honestly Significant Difference) or the corresponding non-parametric Dunn's test (Zar 1999). Data were plotted in ArcGIS (v9.3, ESRI) to examine broad spatial patterns in the fish metrics.

Correlations between fish community metrics (total abundance, total biomass, richness, diversity) with benthic habitat parameters such as depth, rugosity, and percent cover of major benthic groups were examined using non-parametric Spearman's Rho (ρ) coefficients.

In addition, key families and species of commercial and/or ecological interest were selected for further analysis. For each species/family, a summary of the species distribution, mean density among strata, and size frequency is provided. Juveniles/subadults were identified based on length at maturity information provided by FishBase (Froese and Pauly 2008), Garcia-Cagide et al. (1994) and Ault et al. (2008). Fish less than the mean length at maturity were classified as juveniles/subadults. Where length at maturity was unknown, 1/3 of maximum size was used as a proxy (Pittman et al. 2008).

Differences and similarities in species composition were examined using multivariate statistical techniques (Primer v.6, Clarke and Warwick 2001). Data were arranged in a species abundance by site data matrix, which was used to construct a triangular matrix of the percentage similarity in community composition between all pairs of sites using the Bray-Curtis Coefficient. The coefficient is a measure of how similar samples are to each other, ranging from 0% (complete dissimilarity) and 100% (complete similarity). Next, non-metric multidimensional scaling (nMDS) was used to place samples in a two-dimensional configuration such that the rank

order of the distances between the samples agrees with the rank-order of the similarities from the Bray-Curtis matrix. Sites were coded by strata (North/South, 1-5) and hardbottom type for examination of visual patterns of between site similarity. These factors were also used to test for significant differences in similarity using Analysis of Similarities (ANOSIM), a multivariate, non-parametric version of ANOVA. Finally, similarity percentages (SIMPER) were calculated to identify the species that contributed most to the differences between factors.

3.3 RESULTS AND DISCUSSION

Benthic habitat

As expected, hard substrate was the dominant abiotic cover type, with small amounts of sand and rubble (Figure 3.3). The mean maximum height of hard substrate was 31.8 (±2.4 SE) cm.

Turf algae accounted for the highest overall mean percent cover, followed by macroalgae, gorgonians, crustose/calcareous algae, hard coral, and sponges (Figure 3.4, Table 3.3). In general, macroalgal and gorgonian cover tended to be higher in the strata on the western half of the island, while crustose algae became an increasingly abundant component of the community in the eastern strata (Figure 3.5). However, there was a large degree of variability among sites within the same strata. In addition, there was a high degree of variability among sites within the same structure type (Figure 3.6). Sand w/ scattered coral and rock had the highest percentage of uncolonized substrate (67.3 ± 8.1)%, primarily due to the high amount of bare sand found in that bottom type.

Table 3.3. Summary statistics for biotic composition across all Vieques surveys.

Benthic Taxa	Mean (±SE) Percent Cover	Mean (±SE) Height (cm)	Mean (±SE) # Individuals
Live coral	**3.4 (0.5)**		
Montastrea annularis	0.9 (0.3)	x	x
Montastrea cavernosa	0.7 (0.1))	x	x
Porites astreoides	0.4 (0.1)	x	x
Diploria strigosa	0.4 (0.1)	x	x
Siderastrea siderea	0.2 (<0.1)	x	x
Siderastrea radians	0.2 (<0.1)	x	x
Diploria labyrinthiformis	0.1 (<0.1)	x	x
Porites porites	0.1 (<0.1)	x	x
Fire coral (*Millepora sp.*)	0.3 (<0.1)		
Algae	**41.9 (3.3)**		
Turf algae	19.0 (3.3)	x	x
Macroalgae	17.7 (2.6)	4.8 (0.3)	
Crustose algae	4.1 (0.8)	x	x
Cyanobacteria	0.6 (0.1)	0.9 (0.2)	x
Rhodoliths	0.3 (0.3)	<0.1 (<0.1)	x
Filamentous algae	0.2 (0.1)	0.4 (0.1)	x
Gorgonians	**5.9 (0.7)**		
Sea plume/rod/whip	4.6 (0.6)	34.2 (2.8)	5.2 (0.5)
Sea fans	1.1 (0.2)	12.7 (1.7)	0.6 (0.1)
Encrusting gorgonians	0.3 (0.1)	x	x
Sponges	**2.6 (0.3)**		
Barrel/tube/vase	2.0 (0.3)	11.0 (1.1)	2.6 (0.2)
Encrusting	0.7 (0.1)	x	x
Zoanthids	0.1 (<0.1)	x	x
Tunicates	<0.1 (<0.1)	x	x
Anemones	<0.1 (<0.1)	x	<0.1 (<0.1)
Bare substrate	45.7 (3.3)	x	x

Hard coral cover was generally low, with an overall mean of 3.4 (±0.5)%. Mean cover ranged from a high of 6.7 (±1.8)% in the southwestern most stratum (1-South) to less than 2% in the six eastern strata. However, when compared with the other strata, coral cover in 1-South was only significantly different from 4-North and 5-North ($p<0.05$). Coral cover exceeded 10% at four sites, three of which were located on reefs southwest of the island (Figure 3.7). Coral cover was highest on aggregate reef and patch reef structure, and lowest on sand w/ scattered coral and rock (Figure 3.6).

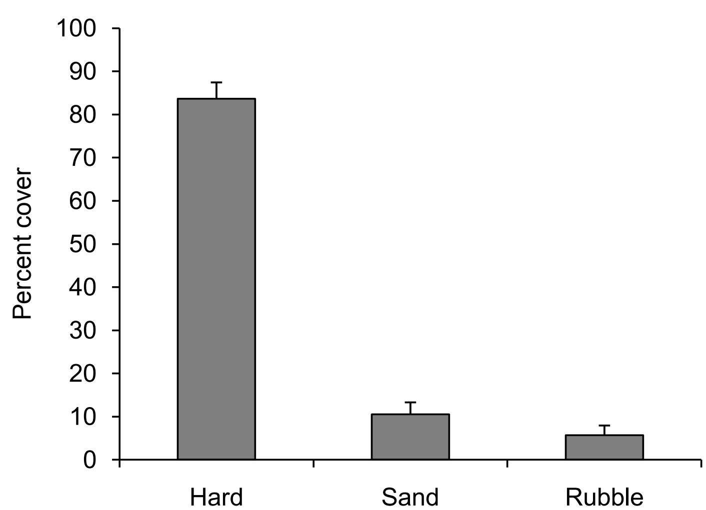


Figure 3.3. Mean (±SE) percent cover of abiotic substrate composition across sites.

The coral community observed in the study was represented by 10 taxonomic families and 26 species. Coral species richness averaged 6.6 (±0.4), with a range of 0-14 species recorded at individual sites (Figure 3.8). Similar to the coral cover variable, species richness was significantly greater in 1-South compared to 4- and 5-North, and in 2-South compared to 5-North ($p<0.05$). The most abundant coral was *Montastrea annularis*, followed by *M. cavernosa*, *Porites*

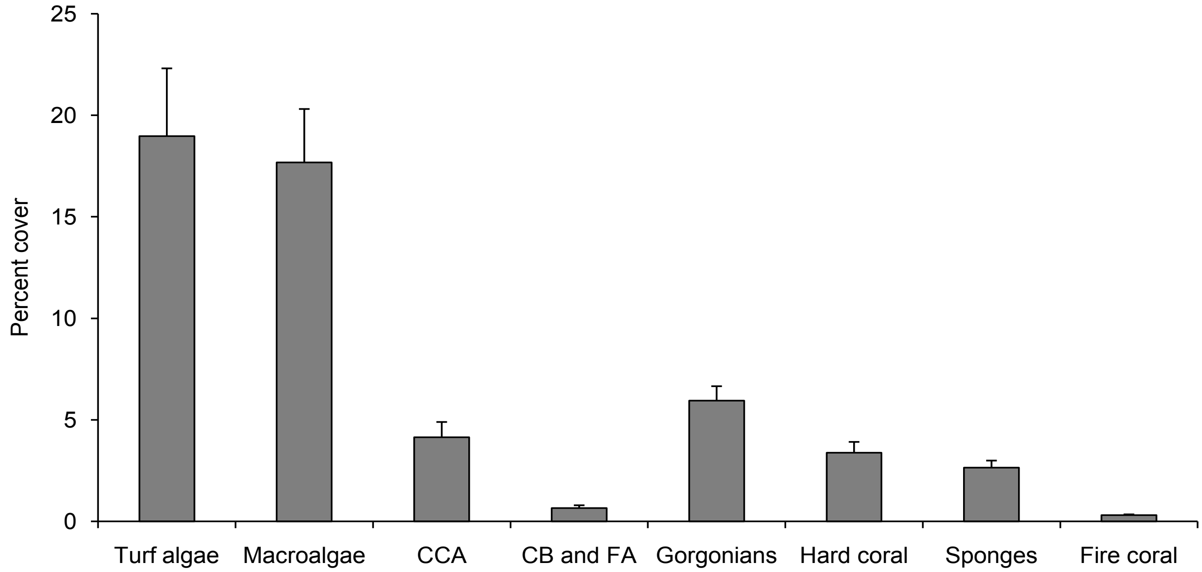


Figure 3.4. Mean (±SE) percent cover for key components of benthic community across sites. CCA = crustose coralline algae; CB and FA = cyanobacteria and filamentous algae.

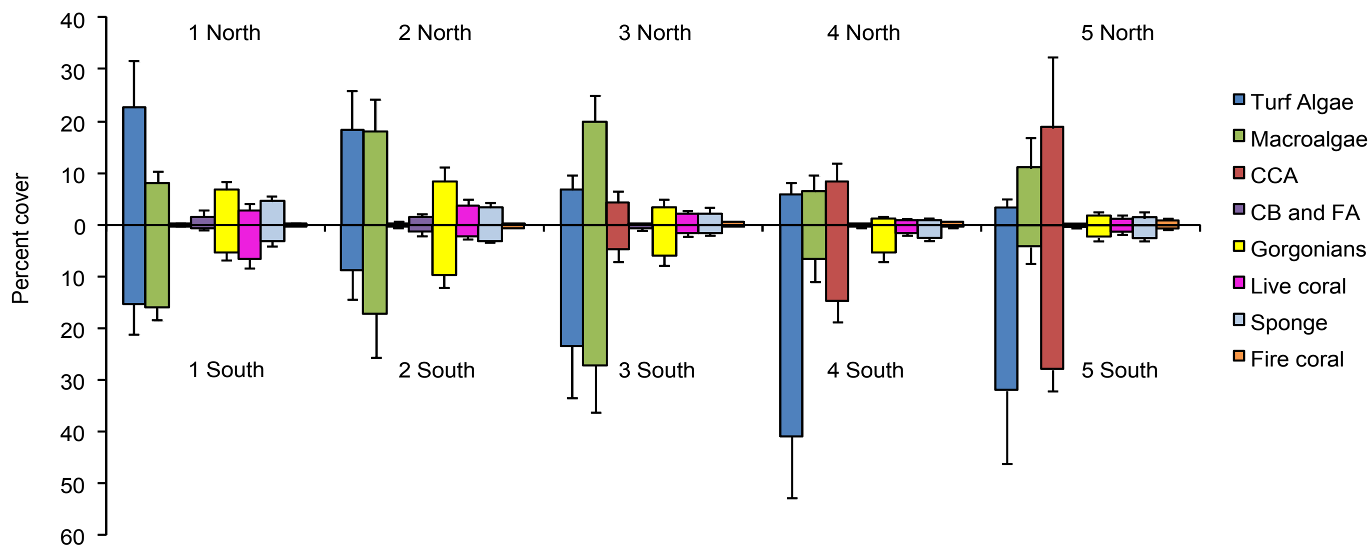


Figure 3.5. Mean (±SE) percent cover for key components of benthic community across strata.

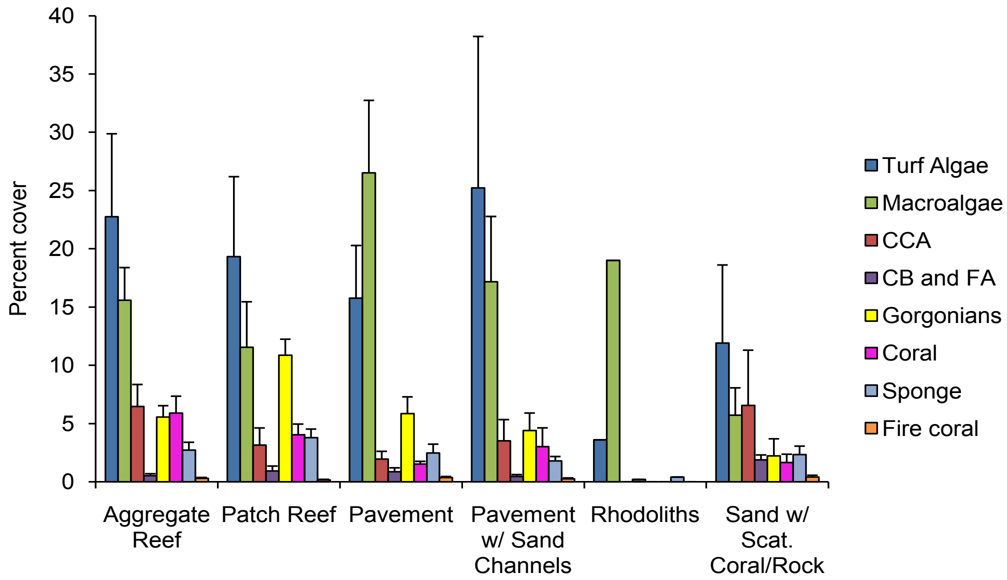


Figure 3.6. Mean (±SE) percent cover for key components of benthic community across hardbottom habitat types.

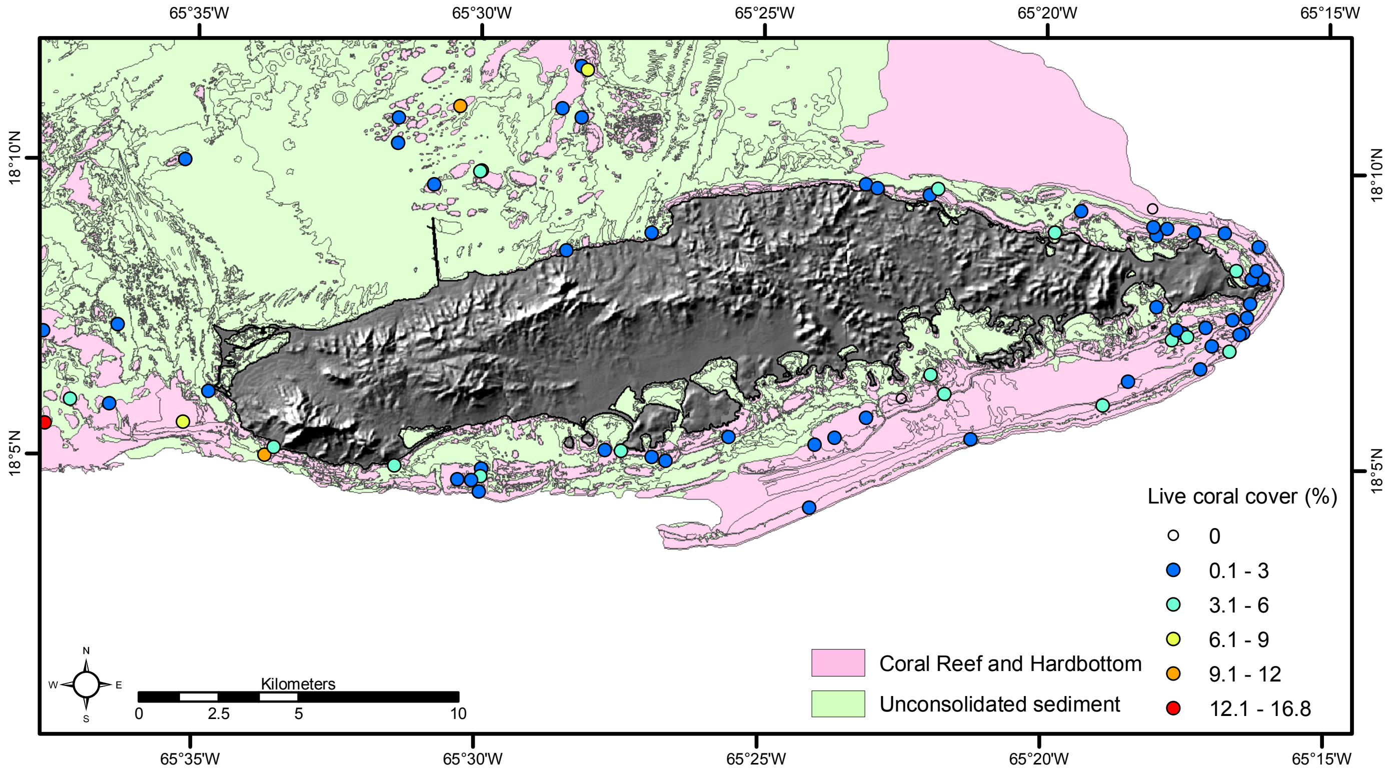


Figure 3.7. Percent live coral cover.

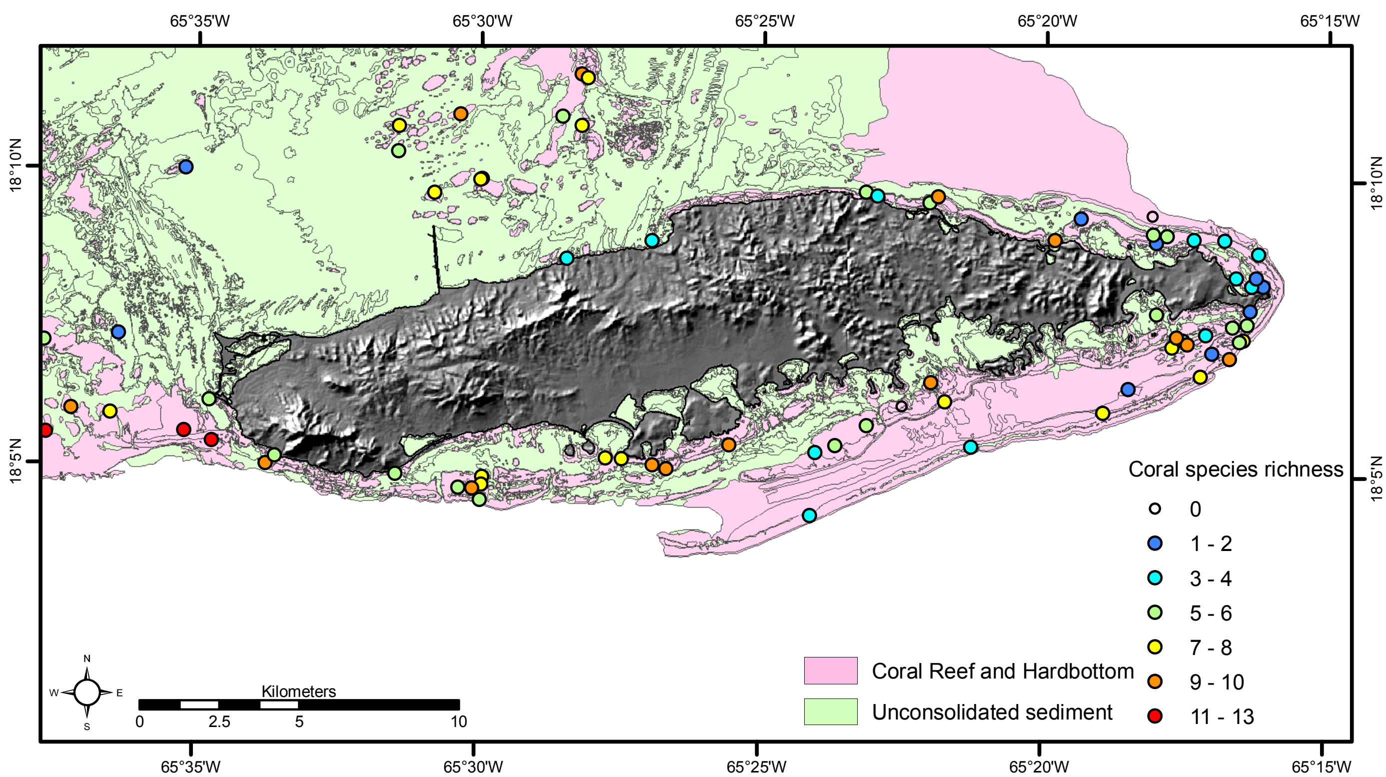


Figure 3.8. Coral species richness.

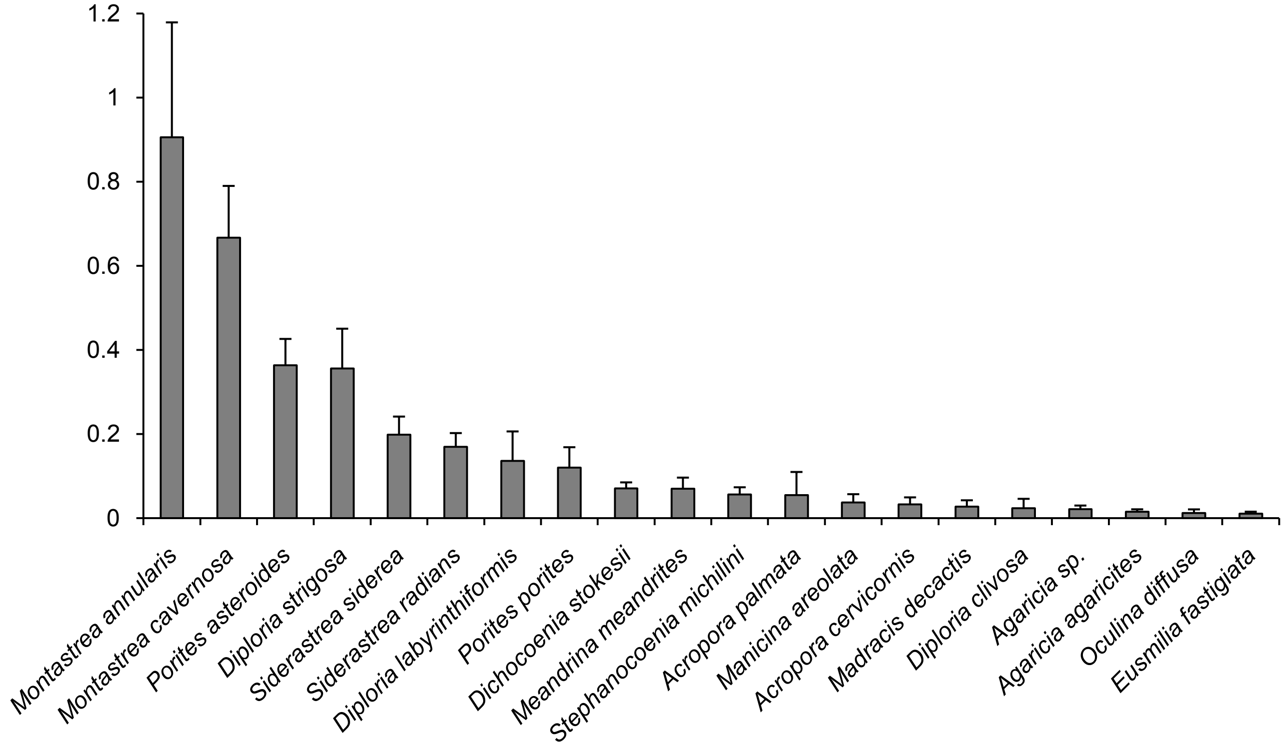


Figure 3.9. Mean (±SE) percent live coral cover of the 20 most abundant coral species on reef/hardbottom across all surveys. Species identified as *Montastrea annularis* refer to the *M. annularis* complex.

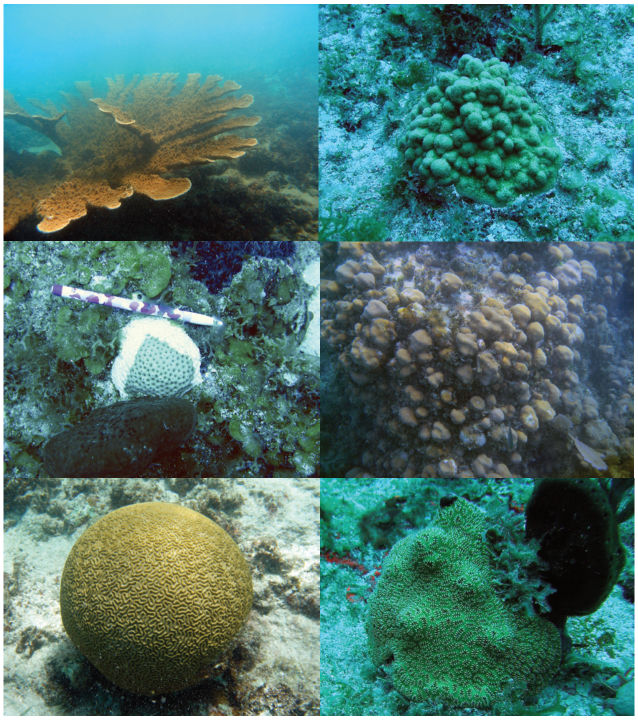


Image 3.4. Clockwise from top-left: *Acropora palmata*, *Porites astreoides*, *Montastrea annularis*, *Dichocoenia stokesi*, *Diploria strigosa,* and *Siderastrea siderea* (partially bleached). Photos: CCMA Biogeography Branch.

astreoides, and *Diploria strigosa* (Figure 3.9). Incidences of bleaching and diseased coral were rare, with each malady occurring in only 4% of the surveyed transects. *Acropora palmata* (elkhorn coral), an important reef-building species that is currently enlisted as threatened under the ESA (Endangered Species Act), was rarely observed, occurring in only one survey. Cover of staghorn coral (*A. cervicornis*) was also low, but the species was more frequently present (12% of surveys) than *A. palmata*.

Mean gorgonian cover was 5.9 (±0.7)% and ranged from 0-25%. Sea plumes/rods/whips were the dominant gorgonian type in terms of both percent cover and number of individuals (Table 3.3), followed by sea fans. Encrusting gorgonians typically made up a small percentage of the benthic community and were recorded at fewer sites than the other gorgonian types. In general, gorgonian cover was higher in the western portion of the study area and decreased further east. The stratum with the highest mean cover was 3-South (Figure 3.5; Figure 3.10), although cover was only significantly greater than the stratum with the lowest mean percent cover, 4-North ($p<0.05$). Gorgonian cover was highest on patch reefs (10.9 ± 1.4)% followed by aggregate reef and pavement, where mean cover was slightly below 6% (Figure 3.6).

Sponge cover averaged 2.6 (±0.3)% and ranged from 0-10.4%. Barrel/tube/vase sponges accounted for the majority of percent cover (2.0 ± 0.3%), while encrusting sponges made up a smaller component of the sponge community (0.7 ± 0.1%). Among strata, the highest cover was found in 1-North, which was significantly greater than cover in 4-North. No other pairwise comparisons were significant, and there were no other distinct spatial patterns in sponge cover (Figure 3.11).

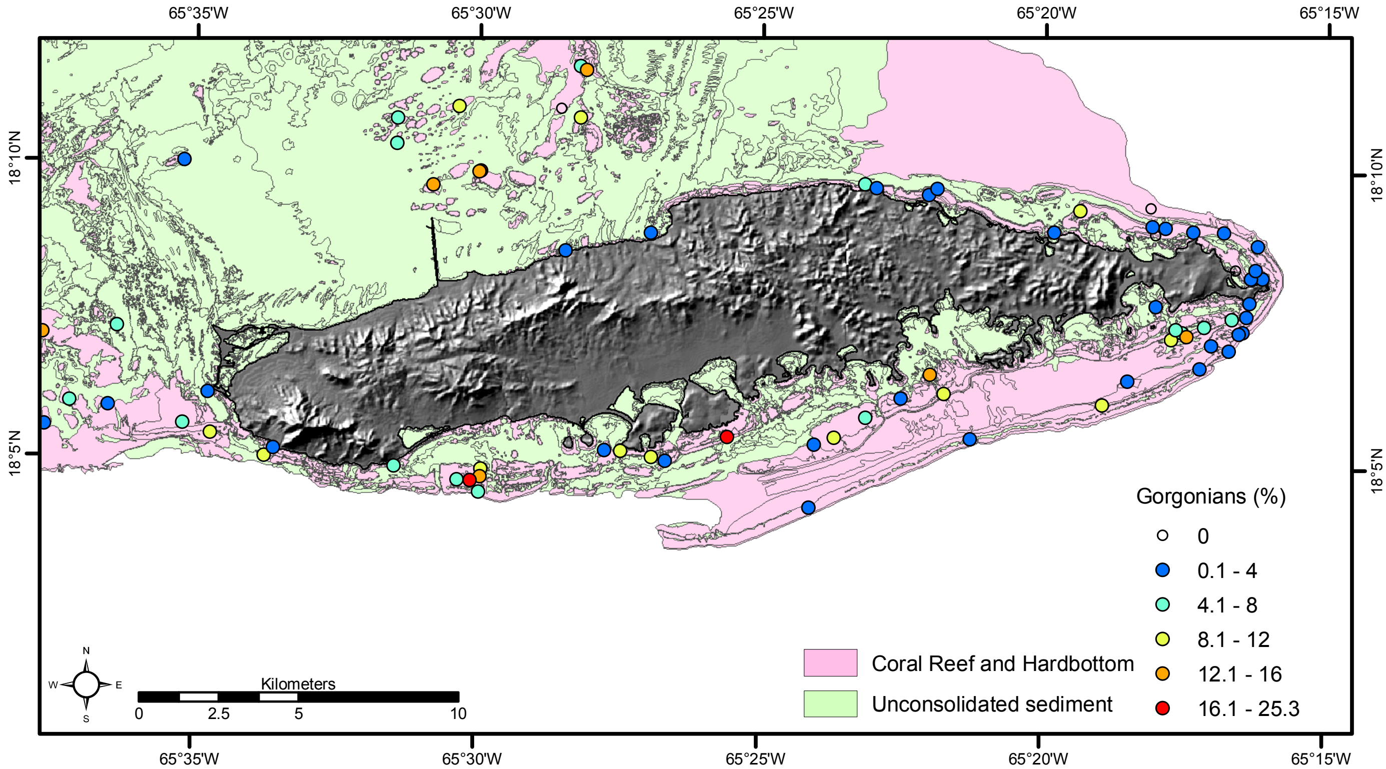


Figure 3.10. Percent gorgonian cover.

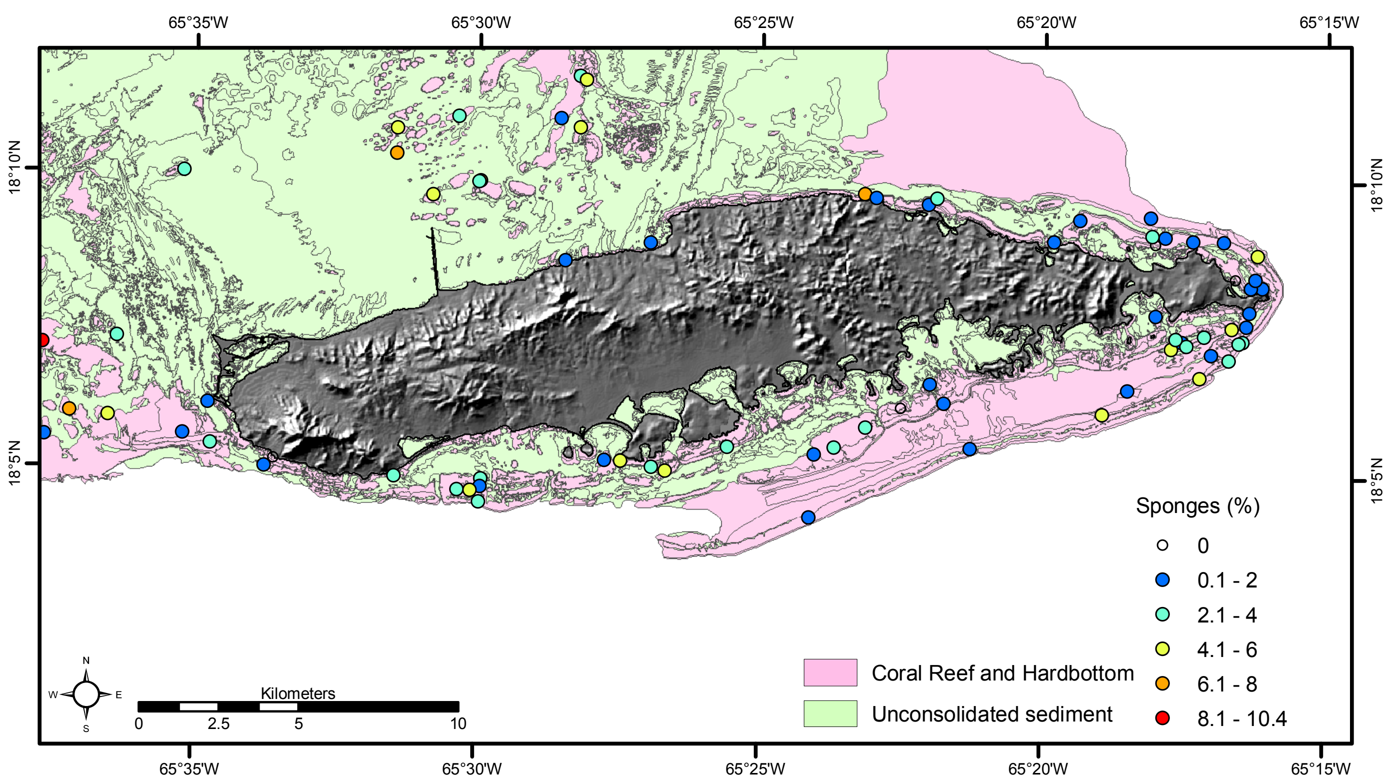


Figure 3.11. Percent sponge cover.

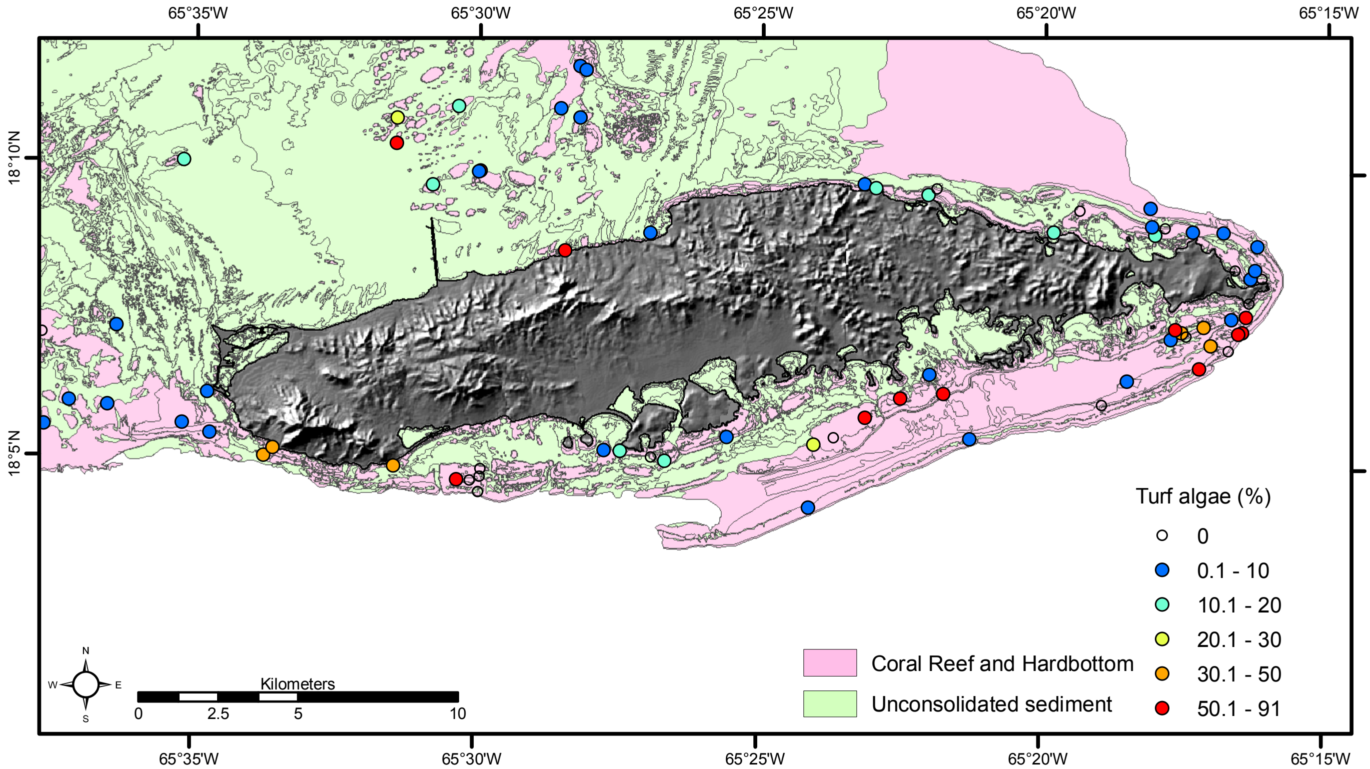


Figure 3.12. Percent turf algae cover.

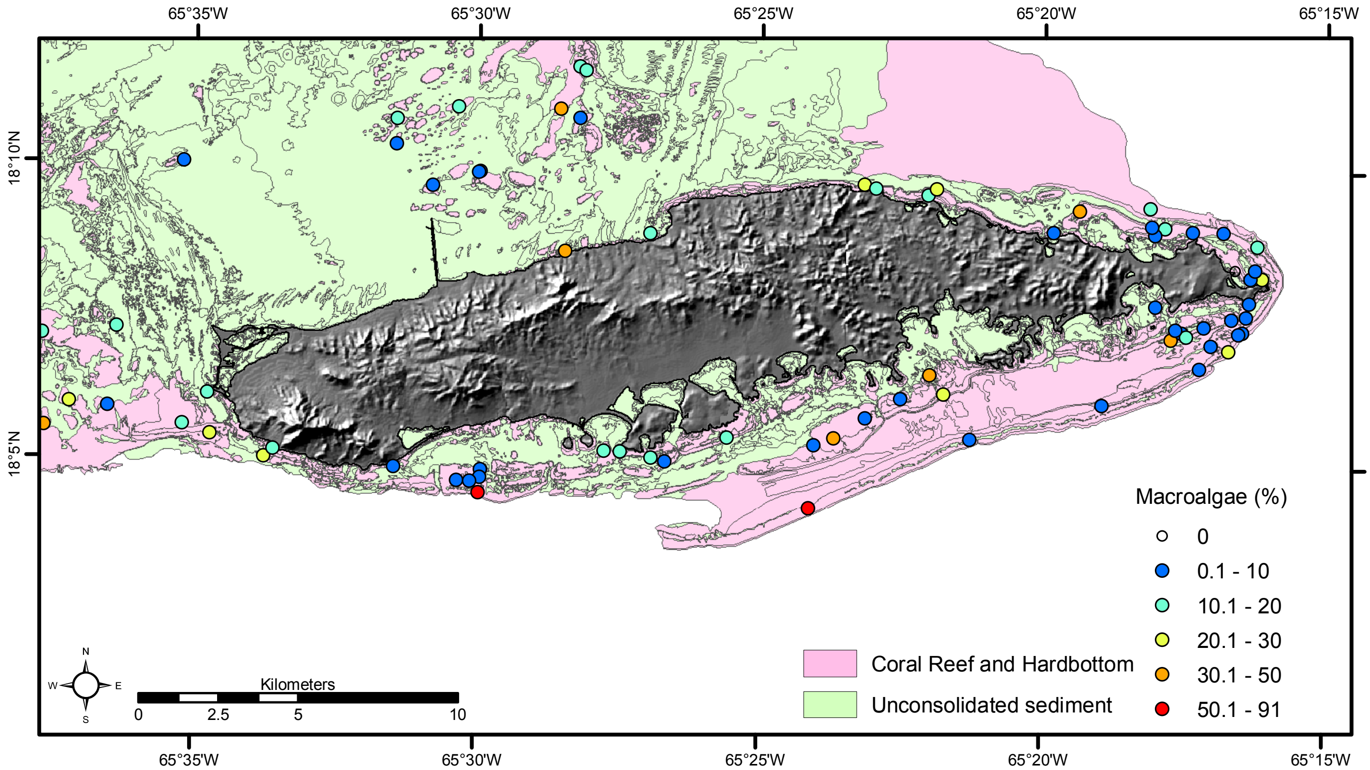


Figure 3.13. Percent macroalgae cover.

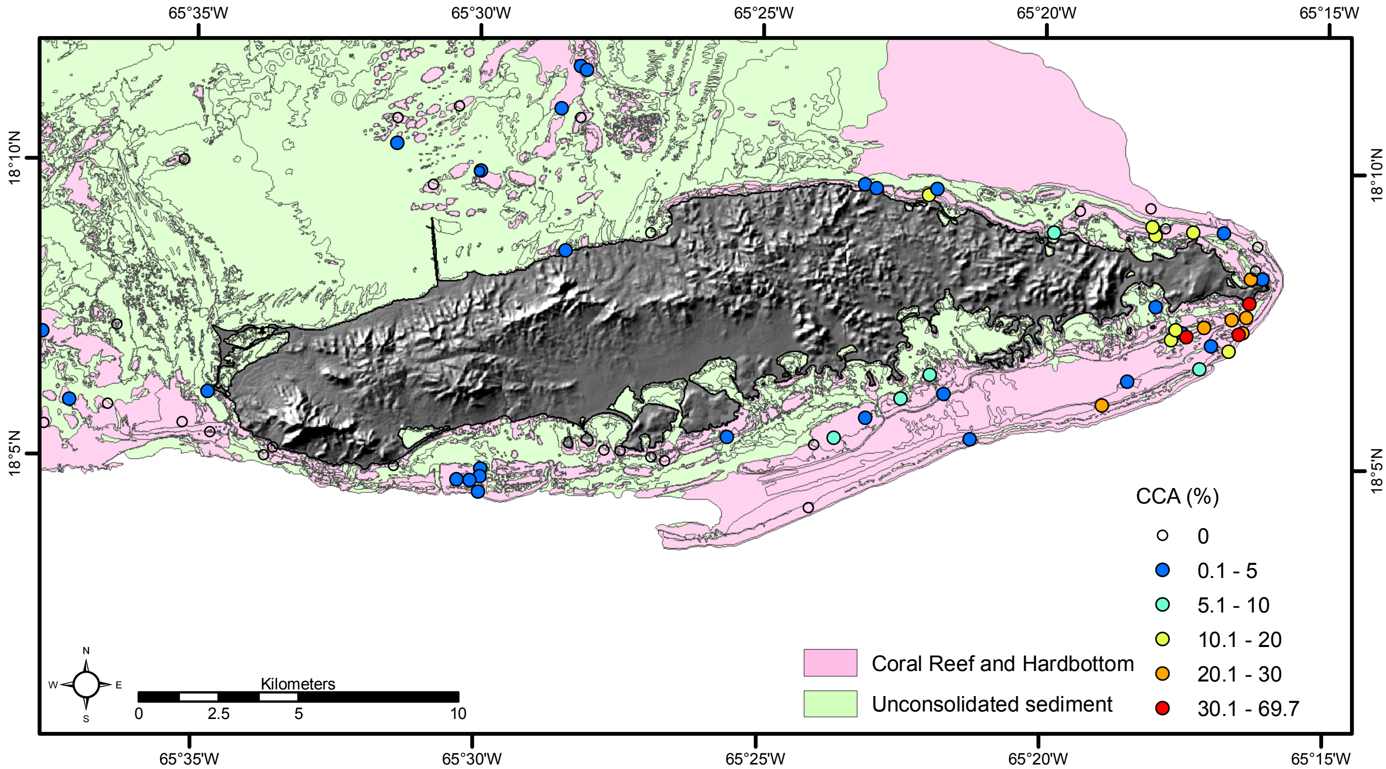


Figure 3.14. Percent crustose coralline algae (CCA) cover.

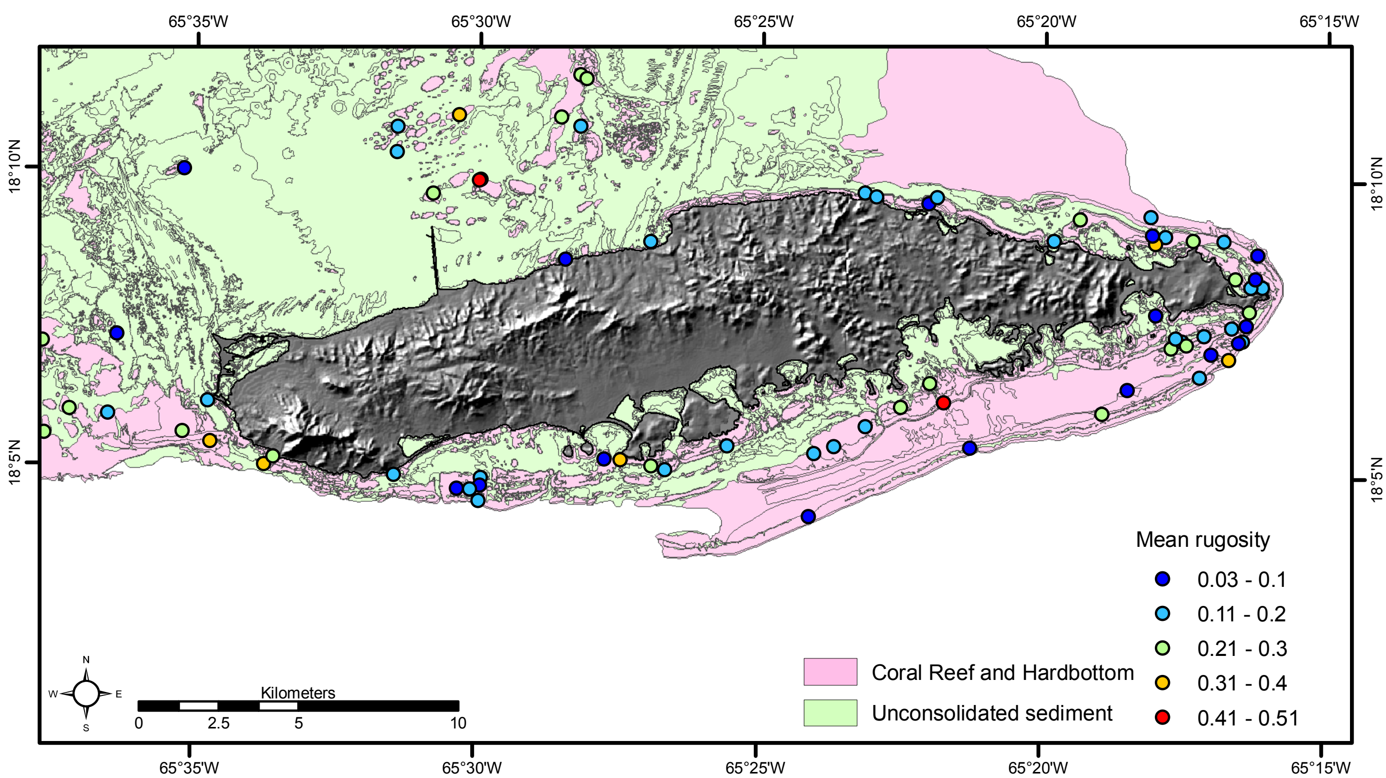


Figure 3.15. Mean rugosity.

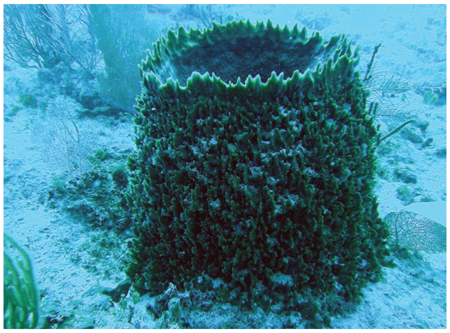


Image 3.5. Barrel sponge. Photo: CCMA Biogeography Branch.

Turf algae was the most dominant algal type in terms of percent cover. Cover averaged 19.0 (±3.3)% and ranged from 0-91% (Figure 3.12). Sites on the south side tended to have higher cover of turf algae than those in northern strata, particularly near the east end of the island. However, there were no significant differences in mean percent cover among strata.

Macroalgal cover averaged 41.9 (±3.3)% and ranged from 0-91.2%. Although there was a large degree of variability, in general macroalgal cover tended to be lower at sites located near the east end of the island (Figures 3.5, 3.13). However, there were no significant differences in percent cover among strata. Among structure types, macroalgae cover was highest on pavement, averaging 26.5 (±6.2)%.

Mean cover of crustose (coralline) algae was 4.1 (±0.8)% and ranged from 0-69.7%. Crustose algae was rare at sites on the western half of the island, but was more prevalent at sites on the eastern end (Figure 3.14). Mean percent cover was significantly greater in 5-South and 4-South when compared to 2-North, 2-South, 1-South, and 1-North. Additionally, cover was significantly higher in 5-South than the 3-South stratum.

Mean rugosity was 0.2 (±0.01) and ranged from 0.03-0.51. There were no distinct spatial patterns in rugosity (Figure 3.15) or significant differences among survey strata. Among structure types, the highest mean rugosity was found on aggregate reef, followed by patch reefs. As expected, less complex habitats (e.g., pavement, sand w/ scattered coral and rock) generally had lower rugosity.

Since 2001, the Biogeography Branch has regularly monitored habitat and reef fish communities using the same survey methodology in other U.S. Caribbean locations, including the Buck Island National Reef Monument in St. Croix (USVI, Pittman et al. 2008), St. John (USVI) and La Parguera in southwestern Puerto Rico (http://ccma.nos.noaa.gov/ecosystems/coralreef/reef_fish.html). Summary data from 2006-2008 was generated for major benthic cover groups for each region to compare with the Vieques findings (Figure 3.16). Although the datasets extend back further, we chose to use only the recent data to be more consistent with the time period in which Vieques was surveyed. In general, levels of benthic cover in Vieques were similar to the other regions, with the exception of slightly lower, but more variable, turf algae cover, and slightly higher crustose algae cover. The higher variability is expected due to the smaller sample size in Vieques. Mean coral cover was similarly low in the other survey locations in comparison to Vieques. Likewise, Riegl et al. (2008) found similarities in the amount of coral cover and coral species assemblages between study locations in Vieques and St. Croix. In contrast to the U.S. Caribbean, mean coral cover at the Flower Garden Banks in the Gulf of Mexico is estimated at 48% (Caldow et al. 2009).

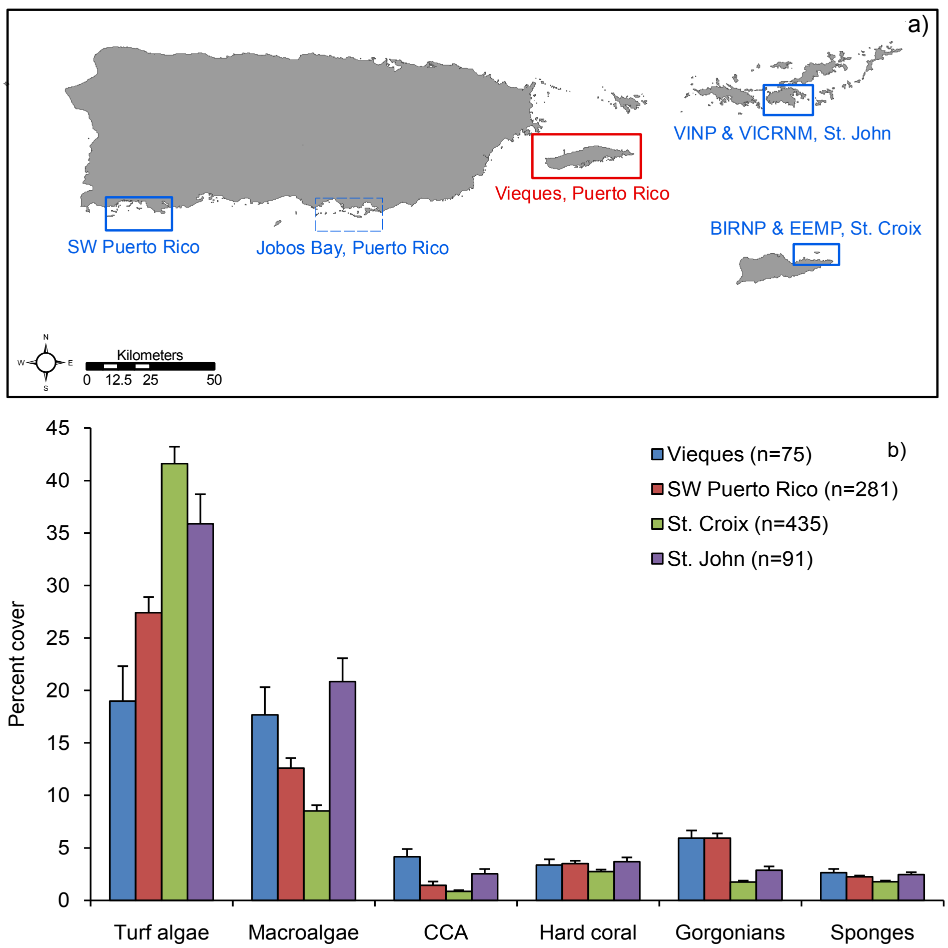


Figure 3.16. a) Locations of CCMA Biogeography Branch monitoring locations. b) Estimated mean (±SE) percent cover of major benthic groups at Vieques in 2007 and other Caribbean monitoring locations (2006-2008). Data from Jobos Bay (2009) was not analyzed at the time of publication of this report.

There have been several previous surveys of hardbottom and reef communities in Vieques that measured coral cover in conjunction with a suite of other habitat and fish variables (e.g., Garcia-Sais et al. 2001, 2004; GMI 2003, 2005; Riegl et al. 2008). These studies have been discussed more comprehensively in Bauer et al. (2008) and are referenced here for comparative purposes only. The most recent studies were primarily restricted to either the east end (GMI 2003, 2005; Riegl et al. 2008) or non-military areas (Garcia-Sais et al. 2001, 2004). These surveys were conducted with different methods (e.g., chain transects, photo transects) making direct comparisons difficult. In addition, it is important to note that all previous studies were conducted before a major bleaching event in 2005. While there are no studies to quantify the extent of the bleaching or resulting change in coral cover around Vieques, widespread bleaching was observed at nearby locations (Clark et al. 2009). At study sites in St. Croix and St. John in the USVI, it was estimated that bleaching and/or disease related mortality resulted in a 36-66% (Lundgren and Hillis-Starr 2008) and 26-48% (Miller et al. 2006) loss in regional coral cover, respectively.

Offshore of former Navy areas on the eastern portion of the island, GMI 2003/Riegl et al. 2008 estimated benthic cover using photo-transects and point count software. Coral cover (including fire coral), measured as the mean relative frequency of benthic point counts, was estimated at 5.5 (±0.9 SE)%. This low cover is consistent with our results, however within the same area (Strata 3 and 4) combined hard coral and fire coral cover did not exceed this amount at any of the sites in the present survey (Figure 3.5, 3.7). While it is unknown how much of this difference can be attributed to variation in survey design and sampling methods, it's possible that coral cover has further declined in this region.

Garcia-Sais et al. (2001, 2004) documented higher coral cover in their study (mean 24.4 ± 3.4% SE and 28.0 ± 2.0%, respectively) in the western portion of the island. The survey locations of Garcia-Sais et al. (2001, 2004) overlapped with Strata 1 and 2 in this survey, where we observed eight out of 10 sites with the highest coral cover. However, live coral cover exceeded 10% at only four of these sites, whereas Garcia-Sais et al. (2001, 2004) observed coral cover exceeding 10% at all but one survey location. It is likely that the primary reason for this large difference is due to site selection and objectives of the study. The previous monitoring locations were selected in areas of "optimal coral growth" following initial canvassing of the survey area (Garcia-Sais et al. 2001), and are permanent sites to be monitored for changes over time. In contrast, sites in the present survey were selected by a stratified-random design and hence are more reflective of average reef/hardbottom habitat throughout Vieques.

Fish Assemblages

Community metrics

The fish community observed in the study consisted of 34 taxonomic families and 110 species (Table 3.4). Fish species richness ranged from five to 34 species per site (100 m^2). Mean species richness was generally higher in the southern than northern strata, although the difference was less pronounced at the western and eastern ends of the island (Figure 3.17), and slightly higher on aggregate reef than other hardbottom types

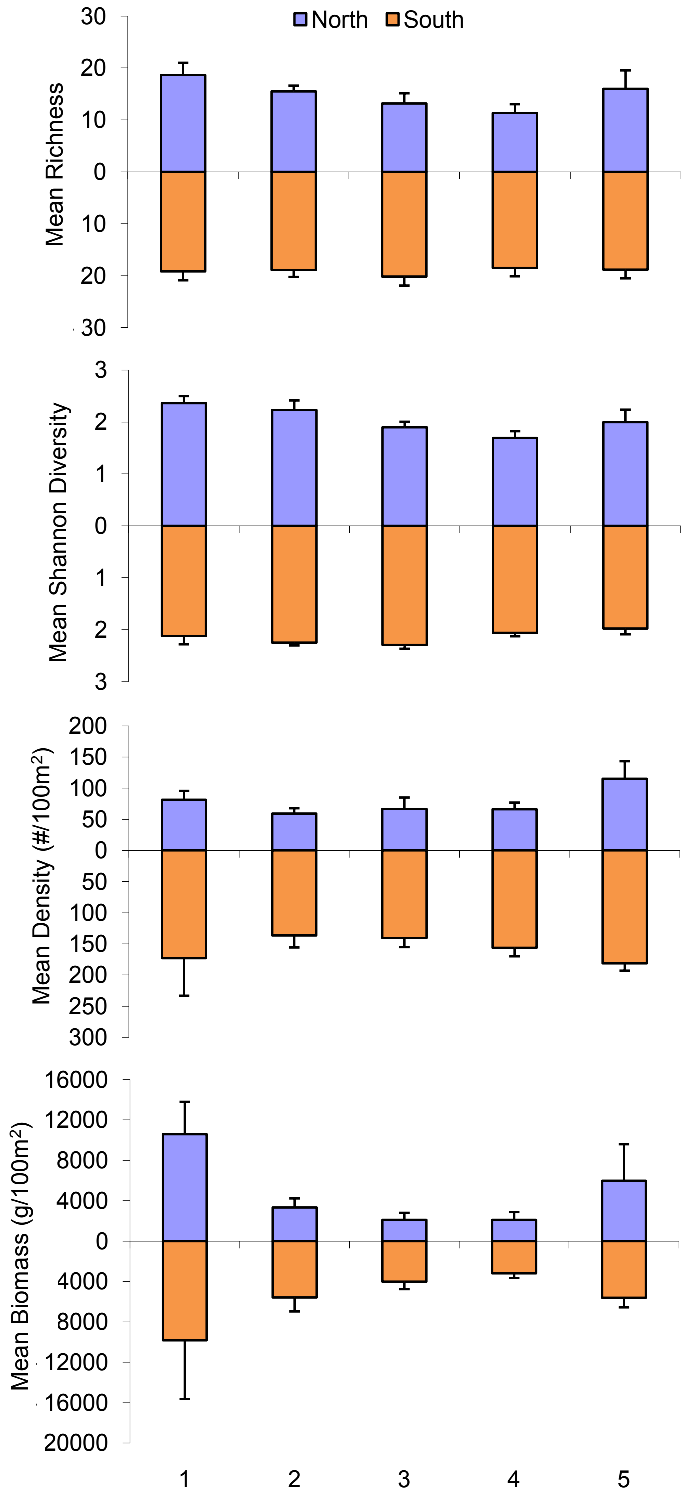


Figure 3.17. Mean (±SE) species richness, Shannon diversity, density, and biomass of fish.

Table 3.4. Mean (+/- SE) frequency, density and biomass for fish species observed at Vieques in the May 2007 survey. H=Herbivore, P=Piscivore, I=Invertivore, Z=Zooplanktivore.

Species	Common Name	Family	Trophic group	% of Surveys	Mean Density (SE)	Mean Biomass (SE)
Abudefduf saxatilis	Sergeant major	Pomacentridae	I	7%	0.20 (0.09)	8.30 (6.14)
Acanthemblemaria spp.	Blenny species	Chaenopsidae	I	7%	0.05 (0.03)	0.02 (0.01)
Acanthostracion quadricornis	Scrawled cowfish	Ostraciidae	I	1%	0.01 (0.01)	0.09 (0.09)
Acanthurus bahianus	Ocean surgeonfish	Acanthuridae	H	89%	6.73 (0.68)	434.29 (64.44)
Acanthurus chirurgus	Doctorfish	Acanthuridae	H	21%	0.44 (0.17)	33.29 (16.86)
Acanthurus coeruleus	Blue tang	Acanthuridae	H	76%	3.95 (0.51)	339.24 (61.78)
Amblycirrhitus pinos	Redspotted hawkfish	Cirrhitidae	Z	4%	0.14 (0.08)	0.02 (0.01)
Anisotremus virginicus	Porkfish	Haemulidae	I	4%	0.06 (0.03)	14.09 (8.99)
Aulostomus maculatus	Trumpetfish	Aulostomidae	P	7%	0.08 (0.04)	6.20 (2.86)
Balistes vetula	Queen triggerfish	Balistidae	I	15%	0.19 (0.09)	140.49 (53.89)
Bodianus rufus	Spanish hogfish	Labridae	I	13%	0.12 (0.04)	19.16 (7.73)
Calamus calamus	Saucereye porgy	Sparidae	I	25%	0.50 (0.19)	87.53 (44.36)
Canthidermis sufflamen	Ocean triggerfish	Balistidae	I	1%	<0.01 (<0.01)	5.51 (5.51)
Canthigaster rostrata	Sharpnose puffer	Tetraodontidae	I	23%	0.44 (0.12)	3.49 (2.34)
Carangoides ruber	Bar jack	Carangidae	P	27%	0.98 (0.57)	14.02 (3.92)
Cephalopholis cruentata	Graysby	Serranidae	P	11%	0.21 (0.09)	26.12 (10.73)
Cephalopholis fulva	Coney	Serranidae	P	23%	0.35 (0.10)	41.45 (13.21)
Chaenopsis limbaughi	Yellowface pikeblenny	Chaenopsidae	I	1%	0.01 (0.01)	0.10 (0.10)
Chaetodon capistratus	Foureye butterflyfish	Chaetodontidae	I	51%	1.30 (0.20)	34.51 (8.41)
Chaetodon ocellatus	Spotfin butterflyfish	Chaetodontidae	I	1%	0.03 (0.03)	1.83 (1.83)
Chaetodon sedentarius	Reef butterflyfish	Chaetodontidae	I	4%	0.04 (0.03)	1.04 (0.75)
Chaetodon striatus	Banded butterflyfish	Chaetodontidae	I	20%	0.28 (0.07)	5.02 (1.74)
Chromis cyanea	Blue chromis	Pomacentridae	Z	27%	4.09 (1.44)	20.74 (6.87)
Chromis multilineata	Brown chromis	Pomacentridae	Z	19%	1.59 (0.72)	3.88 (2.46)
Clepticus parrae	Creole wrasse	Labridae	Z	3%	6.57 (6.28)	515.70 (515.59)
Coryphopterus glaucofraenum	Bridled goby	Gobiidae	H	20%	1.45 (0.84)	1.42 (0.67)
Coryphopterus personatus/ hyalinus	Masked/Glass goby	Gobiidae	H	4%	1.26 (1.09)	0.82 (0.71)
Ctenogobius saepepallens	Dash goby	Gobiidae	H	1%	<0.01 (<0.01)	<0.01 (<0.01)
Decapterus macarellus	Mackerel scad	Carangidae	Z	3%	11.33 (10.96)	901.79 (891.31)
Diodon holocanthus	Balloonfish	Diodontidae	I	1%	0.02 (0.02)	5.55 (5.55)
Epinephelus adscensionis	Rock hind	Serranidae	I	1%	0.01 (0.01)	0.94 (0.94)
Epinephelus guttatus	Red hind	Serranidae	P	29%	0.40 (0.09)	129.77 (43.40)
Gerres cinereus	Yellowfin mojarra	Gerreidae	I	3%	0.04 (0.03)	1.99 (1.61)
Ginglymostoma cirratum	Nurse shark	Ginglymostomatidae	P	1%	<0.01 (<0.01)	<0.01 (<0.01)
Gnatholepis thompsoni	Goldspot goby	Gobiidae	H	15%	0.37 (0.15)	0.38 (0.30)
Gobiosoma evelynae	Sharknose goby	Gobiidae	I	15%	0.28 (0.09)	0.07 (0.02)
Gramma loreto	Fairy basslet	Grammatidae	I	8%	0.21 (0.10)	0.34 (0.21)
Gymnothorax miliaris	Goldentail moray	Muraenidae	P	1%	<0.01 (<0.01)	0.03 (0.03)
Gymnothorax moringa	Spotted moray	Muraenidae	P	1%	<0.01 (<0.01)	<0.01 (<0.01)
Haemulon aurolineatum	Tomtate	Haemulidae	I	1%	0.03 (0.03)	2.93 (2.93)
Haemulon carbonarium	Caesar grunt	Haemulidae	I	7%	0.12 (0.07)	17.05 (8.36)
Haemulon chrysargyreum	Smallmouth grunt	Haemulidae	I	1%	0.03 (0.03)	1.00 (1.00)
Haemulon flavolineatum	French grunt	Haemulidae	I	25%	0.64 (0.16)	59.99 (17.26)
Haemulon plumierii	White grunt	Haemulidae	I	20%	0.92 (0.38)	267.34 (119.39)
Haemulon sciurus	Bluestriped grunt	Haemulidae	I	4%	0.06 (0.04)	8.12 (4.73)
Haemulon spp.	Grunt species	Haemulidae	I	1%	0.03 (0.03)	0.01 (0.01)
Halichoeres bivittatus	Slippery dick	Labridae	I	48%	5.19 (1.40)	19.51 (6.19)
Halichoeres garnoti	Yellowhead wrasse	Labridae	I	64%	5.75 (0.80)	32.74 (4.49)
Halichoeres maculipinna	Clown wrasse	Labridae	I	27%	0.57 (0.16)	0.68 (0.53)
Halichoeres poeyi	Blackear wrasse	Labridae	I	11%	0.13 (0.05)	1.56 (0.89)
Halichoeres radiatus	Puddingwife	Labridae	I	25%	0.26 (0.07)	1.69 (0.71)

Table 3.4. Continued.

Species	Common Name	Family	Trophic group	% of Surveys	Mean Density (SE)	Mean Biomass (SE)
Heteropriacanthus cruentatus	Glasseye snapper	Priacanthidae	Z	1%	0.01 (0.01)	0.85 (0.85)
Holacanthus ciliaris	Queen angelfish	Pomacanthidae	I	1%	0.01 (0.01)	2.06 (2.06)
Holacanthus tricolor	Rock beauty	Pomacanthidae	I	9%	0.10 (0.04)	3.85 (1.70)
Holocentrus adscensionis	Squirrelfish	Holocentridae	I	24%	0.39 (0.11)	48.20 (15.52)
Holocentrus rufus	Longspine squirrelfish	Holocentridae	I	49%	1.38 (0.53)	114.26 (43.44)
Hypoplectrus chlorurus	Yellowtail hamlet	Serranidae	I	1%	0.02 (0.02)	0.06 (0.06)
Hypoplectrus indigo	Indigo hamlet	Serranidae	I	1%	0.02 (0.02)	0.43 (0.43)
Hypoplectrus nigricans	Black hamlet	Serranidae	P	3%	0.03 (0.03)	0.68 (0.55)
Hypoplectrus puella	Barred hamlet	Serranidae	I	7%	0.14 (0.06)	2.35 (1.52)
Hypoplectrus spp.	Hamlet species	Serranidae	I	4%	0.06 (0.04)	0.65 (0.53)
Hypoplectrus unicolor	Butter hamlet	Serranidae	P	7%	0.08 (0.04)	1.68 (0.93)
Kyphosus sectator	Chub (Bermuda/Yellow)	Kyphosidae	H	1%	0.01 (0.01)	6.68 (6.68)
Lachnolaimus maximus	Hogfish	Labridae	I	12%	0.15 (0.05)	16.23 (7.00)
Lactophrys triqueter	Smooth trunkfish	Ostraciidae	I	8%	0.08 (0.03)	10.38 (4.80)
Lutjanus analis	Mutton snapper	Lutjanidae	I	5%	0.04 (0.02)	33.85 (20.64)
Lutjanus apodus	Schoolmaster	Lutjanidae	P	12%	0.38 (0.21)	73.58 (56.82)
Lutjanus griseus	Gray snapper	Lutjanidae	P	4%	0.03 (0.01)	2.98 (1.80)
Lutjanus jocu	Dog snapper	Lutjanidae	P	1%	0.02 (0.02)	36.92 (36.93)
Lutjanus mahogoni	Mahogany snapper	Lutjanidae	P	1%	0.02 (0.02)	4.53 (4.53)
Lutjanus synagris	Lane snapper	Lutjanidae	P	3%	0.02 (0.01)	4.37 (3.44)
Malacanthus plumieri	Sand tilefish	Malacanthidae	I	8%	0.10 (0.05)	26.06 (12.75)
Malacoctenus macropus	Rosy blenny	Labrisomidae	I	7%	0.13 (0.08)	0.31 (0.23)
Malacoctenus triangulatus	Saddled blenny	Labrisomidae	I	8%	0.09 (0.04)	0.02 (0.01)
Melichthys niger	Black durgon	Balistidae	H	7%	0.19 (0.17)	68.51 (59.72)
Microspathodon chrysurus	Yellowtail damselfish	Pomacentridae	H	15%	0.47 (0.21)	27.32 (14.45)
Mulloidichthys martinicus	Yellow goatfish	Mullidae	I	5%	0.18 (0.12)	17.55 (12.51)
Mycteroperca tigris	Tiger grouper	Serranidae	P	1%	0.03 (0.03)	27.80 (27.80)
Myripristis jacobus	Blackbar soldierfish	Holocentridae	I	5%	0.06 (0.03)	10.64 (6.52)
Nes longus	Orangespotted goby	Gobiidae	I	5%	0.42 (0.29)	9.92 (9.44)
Ocyurus chrysurus	Yellowtail snapper	Lutjanidae	I	69%	2.76 (0.50)	359.77 (112.91)
Ophioblennius macclurei	Redlip blenny	Blenniidae	H	12%	0.34 (0.15)	1.09 (0.55)
Opistognathus aurifrons	Yellowhead jawfish	Opistognathidae	Z	8%	0.32 (0.16)	1.13 (0.58)
Pareques acuminatus	Highhat	Sciaenidae	I	1%	0.01 (0.01)	0.61 (0.61)
Pomacanthus arcuatus	Gray angelfish	Pomacanthidae	I	21%	0.34 (0.08)	137.66 (37.24)
Pomacanthus paru	French angelfish	Pomacanthidae	I	16%	0.45 (0.24)	174.02 (84.19)
Prognathodes aculeatus	Longsnout butterflyfish	Chaetodontidae	I	1%	0.01 (0.01)	0.10 (0.10)
Pseudupeneus maculatus	Spotted goatfish	Mullidae	I	28%	0.51 (0.13)	26.55 (7.91)
Scarus iseri	Striped parrotfish	Scaridae	H	32%	2.86 (0.89)	51.67 (19.72)
Scarus taeniopterus	Princess parrotfish	Scaridae	H	47%	3.54 (0.71)	186.92 (44.34)
Scarus vetula	Queen parrotfish	Scaridae	H	4%	0.06 (0.03)	6.64 (4.23)
Scomberomorus regalis	Cero	Scombridae	P	1%	0.03 (0.03)	16.94 (16.94)
Serranus baldwini	Lantern bass	Serranidae	I	7%	0.15 (0.08)	0.78 (0.44)
Serranus tabacarius	Tobaccofish	Serranidae	P	5%	0.12 (0.07)	2.63 (1.50)
Serranus tigrinus	Harlequin bass	Serranidae	I	28%	0.71 (0.15)	8.47 (2.01)
Serranus tortugarum	Chalk bass	Serranidae	Z	4%	0.50 (0.42)	3.20 (2.17)
Sparisoma atomarium	Greenblotch parrotfish	Scaridae	H	8%	0.31 (0.19)	0.53 (0.44)
Sparisoma aurofrenatum	Redband parrotfish	Scaridae	H	91%	8.63 (0.78)	330.17 (51.39)
Sparisoma rubripinne	Yellowtail parrotfish	Scaridae	H	11%	0.25 (0.10)	33.49 (16.53)
Sparisoma viride	Stoplight parrotfish	Scaridae	H	65%	2.19 (0.31)	348.57 (72.71)
Sphoeroides testudineus	Checkered puffer	Tetraodontidae	I	1%	0.02 (0.02)	0.86 (0.86)
Sphyraena barracuda	Great barracuda	Sphyraenidae	P	15%	0.21 (0.07)	206.75 (122.08)
Stegastes adustus	Dusky damselfish	Pomacentridae	H	17%	0.48 (0.17)	2.78 (1.18)
Stegastes diencaeus	Longfin damselfish	Pomacentridae	H	17%	0.61 (0.30)	6.13 (2.83)

Table 3.4. Continued.

Species	Common Name	Family	Trophic group	% of Surveys	Mean Density (SE)	Mean Biomass (SE)
Stegastes leucostictus	Beaugregory	Pomacentridae	H	19%	0.31 (0.10)	2.17 (0.85)
Stegastes partitus	Bicolor damselfish	Pomacentridae	H	79%	15.72 (1.50)	25.43 (4.42)
Stegastes planifrons	Threespot damselfish	Pomacentridae	H	13%	0.36 (0.13)	1.87 (1.00)
Stegastes variabilis	Cocoa damselfish	Pomacentridae	H	4%	0.03 (0.02)	0.02 (0.01)
Thalassoma bifasciatum	Bluehead	Labridae	I	83%	26.69 (2.95)	40.12 (6.17)
Xyrichtys splendens	Green razorfish	Labridae	Z	3%	0.12 (0.11)	0.47 (0.47)

(Figure 3.18). Richness in 3-South was significantly greater than 4-North ($p<0.05$); no other pairwise comparisons were significant. Of the 31 sites on the north side of the island, richness only exceeded 20 at three locations (10%), while >20 species were documented at 16 of the 44 locations on the south side (36%) (Figure 3.19).

Shannon diversity (H') ranged from 1.04-2.88. Similar to the richness metric, diversity was significantly lower in 4-North when compared to 3-South ($p<0.05$); no other pairwise comparisons were significant. Although there were no distinct spatial patterns, diversity "hotspots" included patch reefs on the northwestern side of the island and aggregate reef in the southwest region (Figure 3.20).

Overall, total fish density tended to differ on a north-south rather than east-west gradient (Figure 3.17, 3.21). In general, fish density was lower on the north side of the island compared to the south side. Density in 4-South and 5-South were significantly greater compared to all northern strata with the exception of 5-north. In addition, density was significantly greater in 3-South compared to 2-, 3-, and 4-North, and in 2-South compared to 2-North. The large standard error of mean density in 1-South was primarily due to a large school of mackerel scad (*Decapterus macarellus*) at one site.

Although biomass also tended to be higher on the south side and at the eastern and western ends of the island, there was a high degree of variability in some strata (Figure 3.17, 3.22). A Kruskal-Wallis test indicated that biomass was not significantly different among strata ($p = 0.068$). Again, the high mean and standard error in 1-South was partly due to the school of *D. marcarellus*. Similarly, individual sites in 1-North and 5-North with high biomass influenced the high variability in those strata.

Results of the nMDS and ANOSIM analysis indicate that fish assemblages differed among strata (Figure 3.23). In particular, there was a strong north-south effect. Southern sites on the

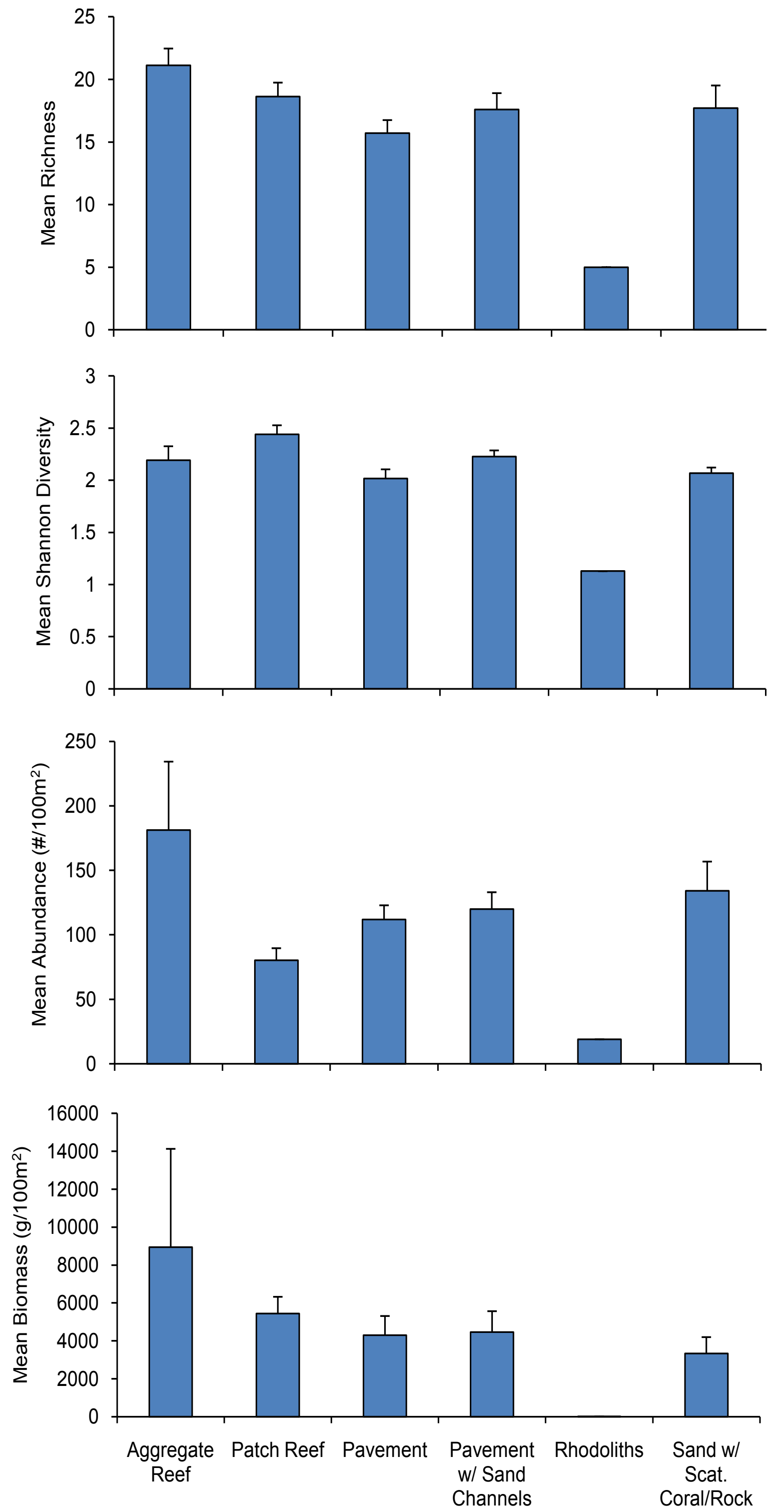


Figure 3.18. Mean (±SE) species richness, Shannon diversity, density, and biomass across hardbottom habitat type in the Vieques 2007 survey.

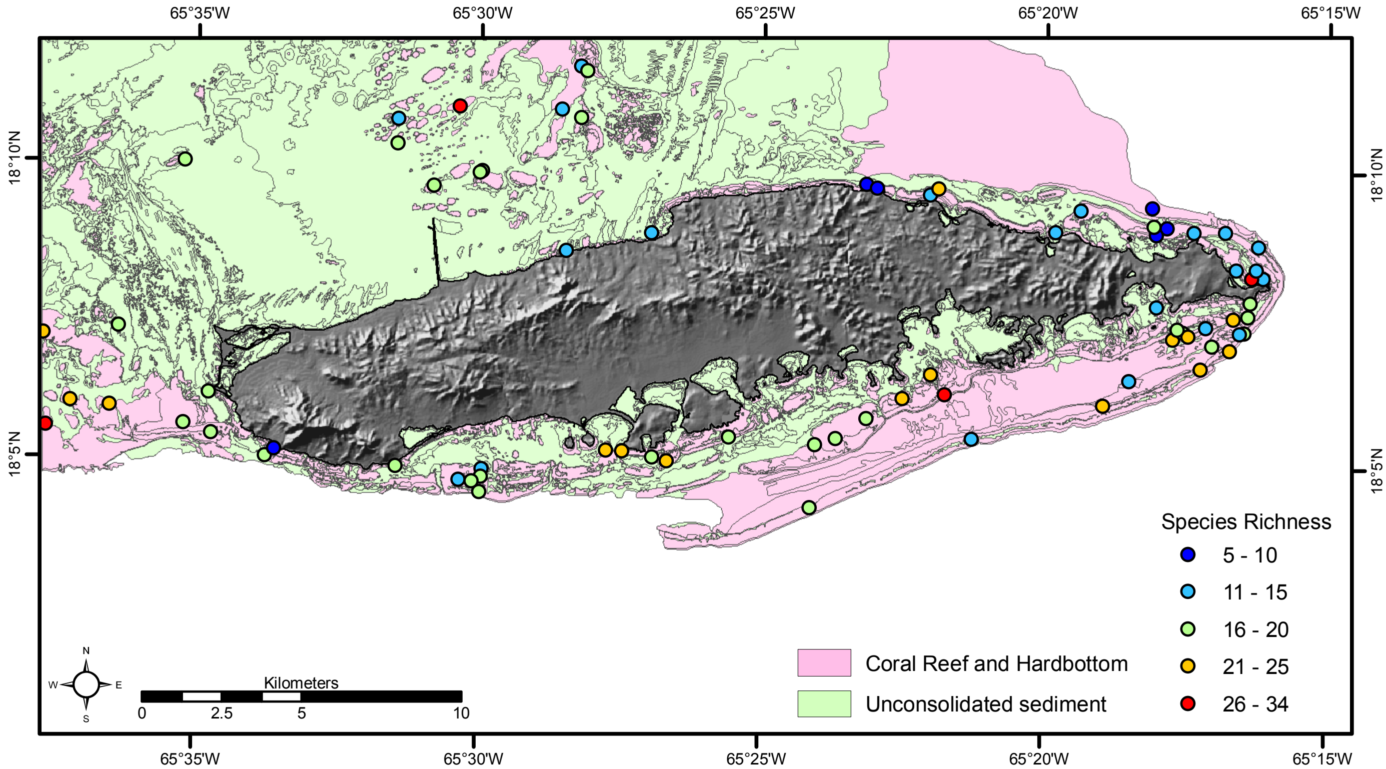


Figure 3.19. Fish species richness.

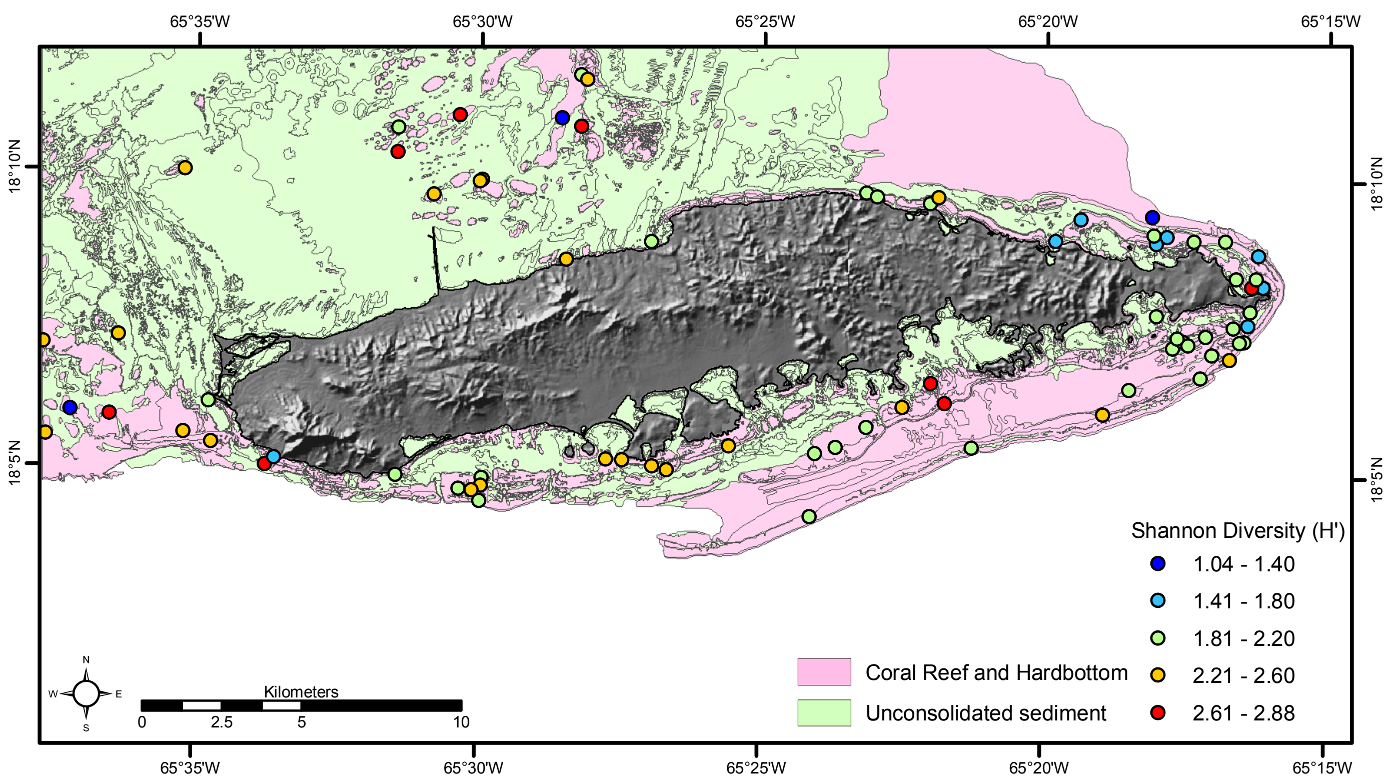


Figure 3.20. Fish species diversity.

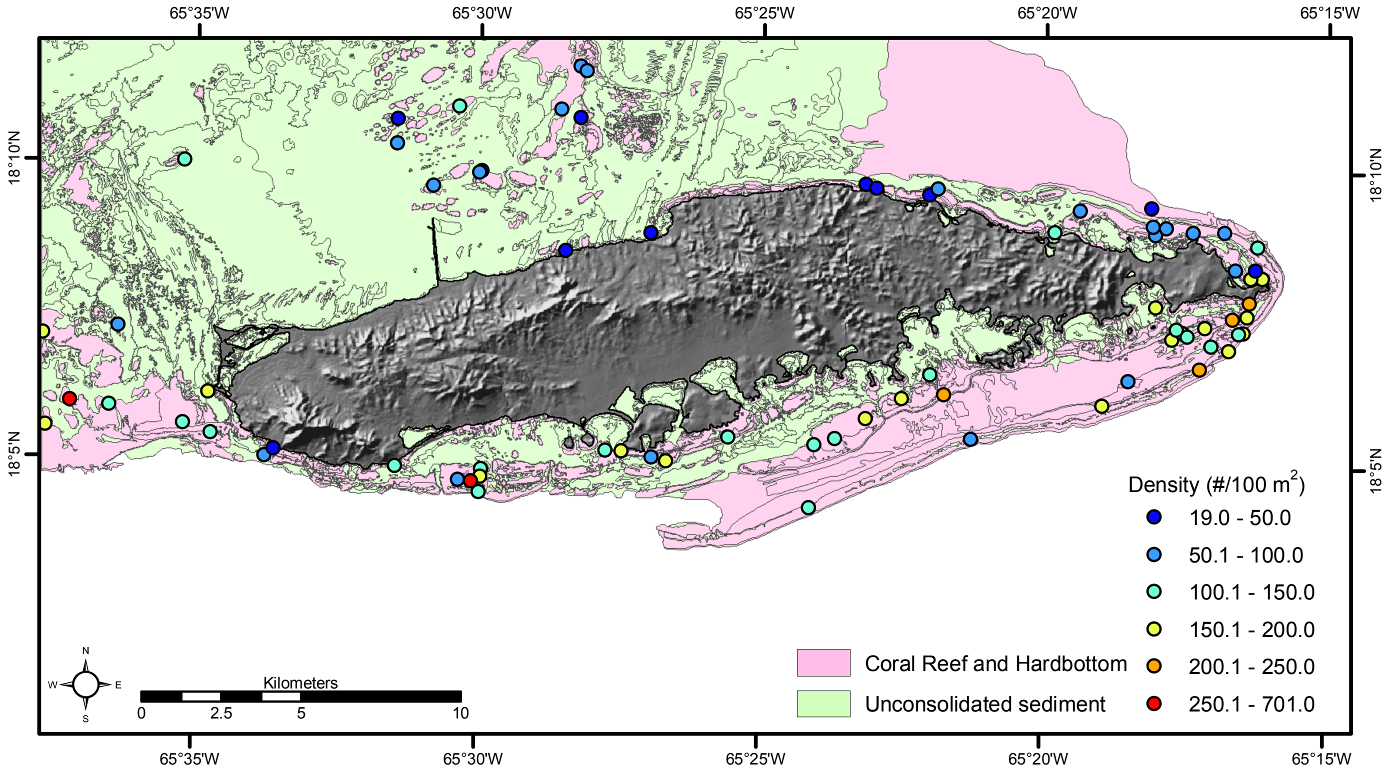


Figure 3.21. Total fish density.

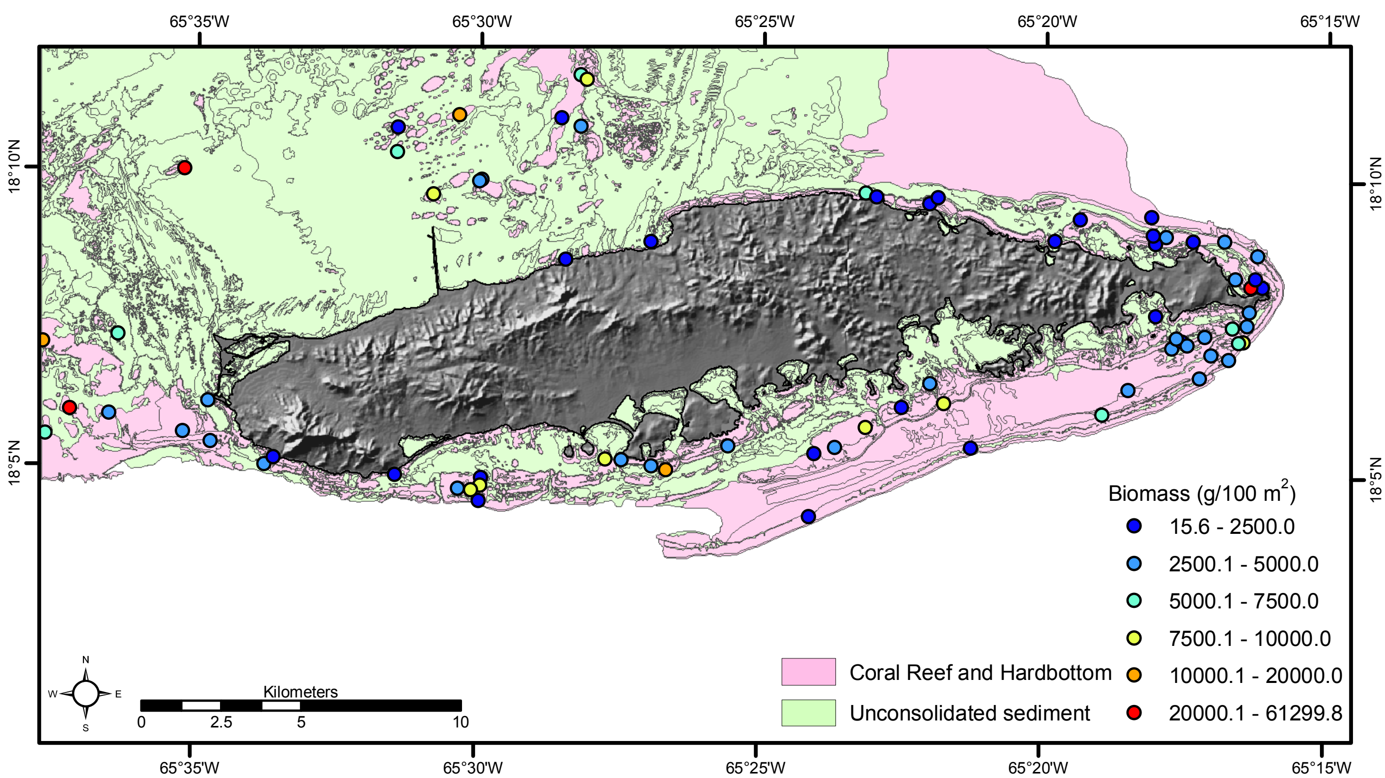


Figure 3.22. Total fish biomass.

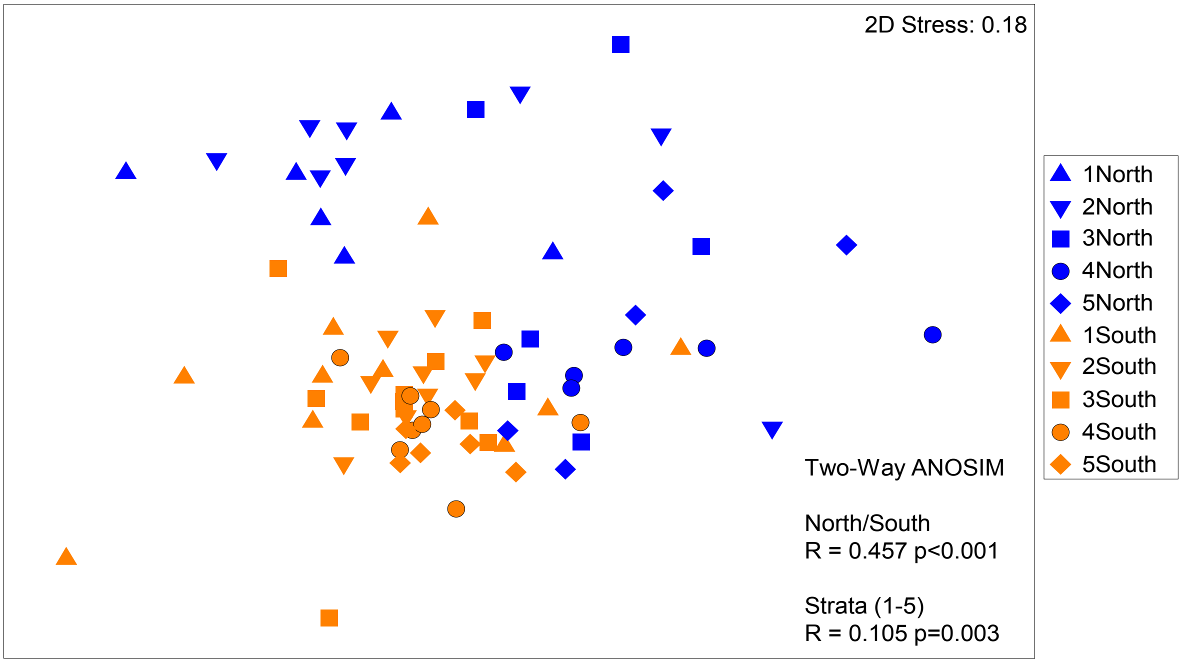


Figure 3.23. Non-metric multidimensional scaling ordination based on between site similarity in fish community composition using fish abundance data. Sites are color-coded by north/south proximity.

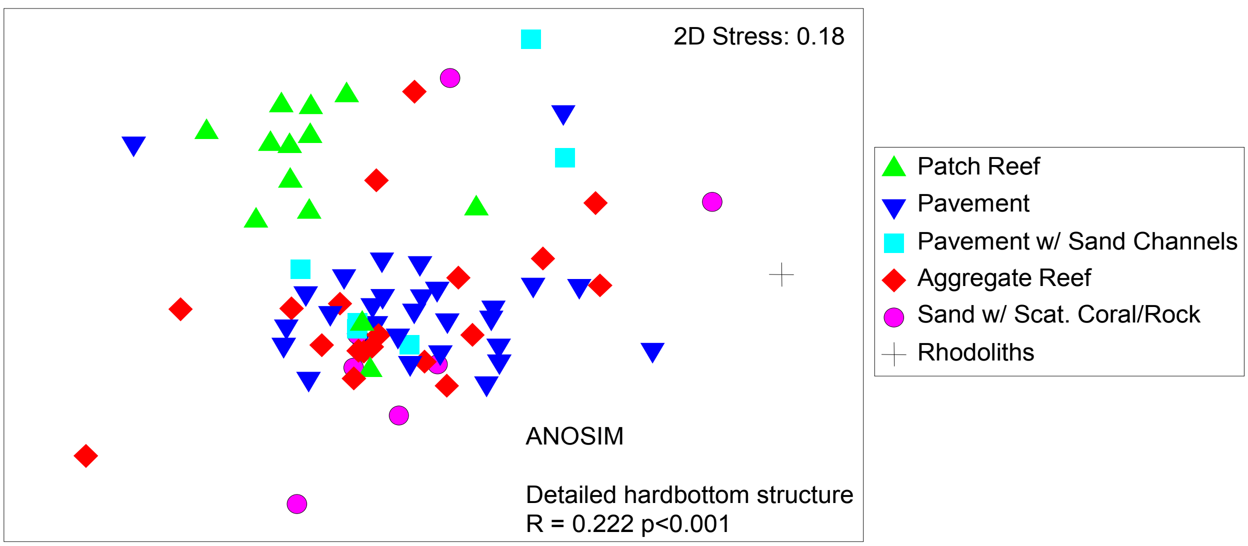


Figure 3.24. Non-metric multidimensional scaling ordination based on between site similarity in fish community composition using fish abundance data. Sites are color-coded by hardbottom habitat type.

nMDS plot formed a more compact group of similar sites. In contrast, northern sites tended to be more dispersed, although sites within strata 1- and 2-North were more similar to each other. Results of the ANOSIM analysis indicated that both the north/south and east-west (i.e., 1-5) strata factors were statistically significant, but the higher R value for the north/south factor (0.457, vs. 0.105 for the 1-5 strata effect) indicates that this factor is more evident. Pairwise tests for differences between strata 1-5 indicated that there were significant differences between communities in strata 1 vs. 3 and 4, and strata 2 vs. 4 and 5.

At least part of the differences in fish community structure among strata, particularly on the north vs. the south side of the island, appears to be associated with hardbottom structure (Figure 3.24). The spatial distribution of benthic habitats around Vieques is heterogeneous; as a result, the distribution of survey sites according to their detailed hardbottom type is also uneven around the island. For example, 14 surveys were conducted on higher complexity aggregate reef on the south side, compared to 5 on the north side. In contrast, patch reef structure is more prevalent on the north side, and 10 of the 13 patch reef survey sites were located in the five northern strata. The nMDS plot revealed some separation by habitat type, particularly for patch reefs and pavement. Aggregate reef sites tended to be more scattered but many shared high similarity with each other and the pavement group. Pavement communities tended to cluster together regardless of whether they were located

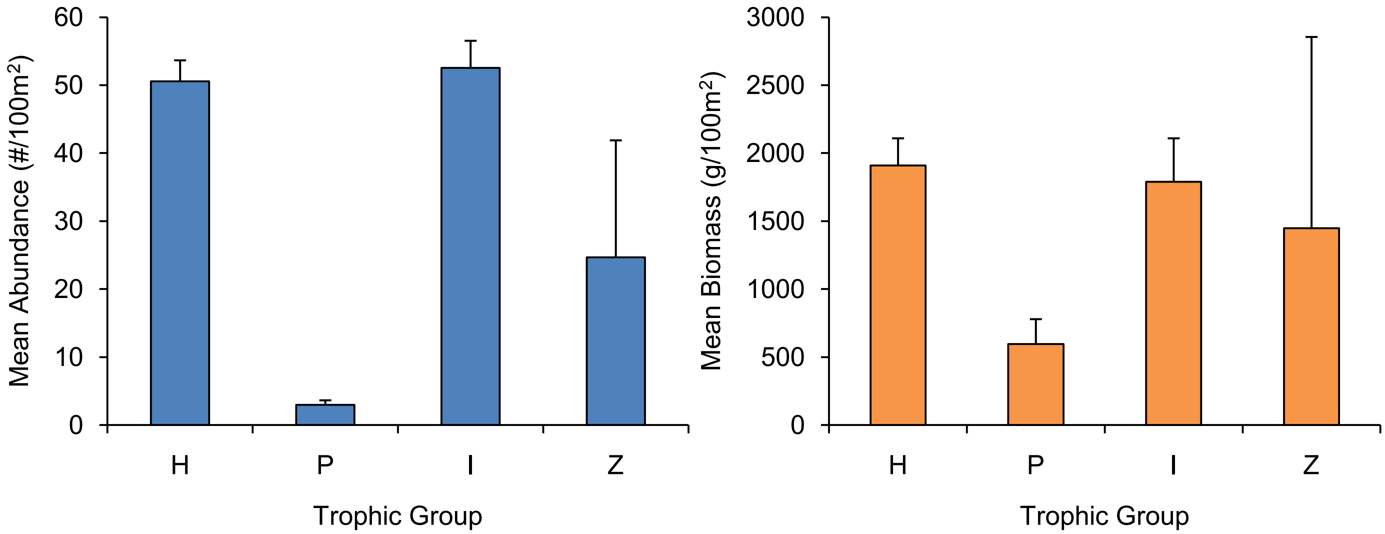


Figure 3.25. Mean (±SE) density (a) and biomass (b) of major trophic groups across surveys. H=Herbivore, P=Piscivore, I=Invertivore, Z=Zooplanktivore.

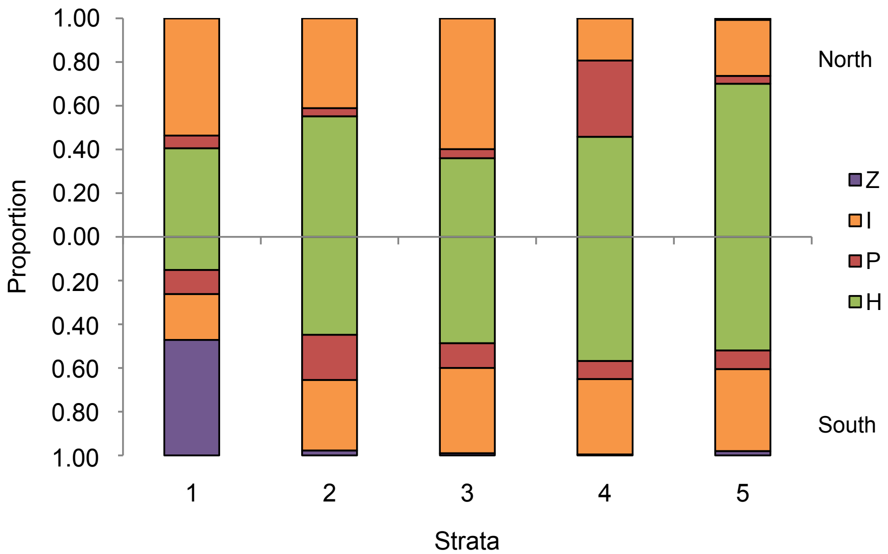


Figure 3.26. Proportional biomass of trophic groups across survey strata.

Image 3.6. Gray angelfish (*Pomacanthus arcuatus*). Photo: CCMA Biogeography Branch.

on the north or south shore. However, within pavement sites, there was still a clear split between the northern and southern pavement sites, indicating that a factor other than habitat type is driving some of the dissimilarity between the north and south shores. Other potential factors that could account for this pattern include differences in depth, exposure to currents, wave action, and hydrodynamics between the north and south sides of the island. For example, depth was positively correlated with several fish metrics, including total density (Spearman's Rho=0.25).

Similarity percentages were calculated to examine which species accounted for similarities/dissimilarities among and between groups. In general, the most abundant species appear to contribute to the largest similarities among groups and dissimilarities between groups. For example, although *Thalassoma bifasciatum* was abundant across all strata and hardbottom types, the mean abundance of this species was nearly twice as high in the southern strata compared to the north, and nearly three times higher on pavement and aggregate reef compared to patch reef. Several outliers are apparent on the nMDS plots. These survey points included sites with both the lowest and highest total fish abundance (4N01 and 1S10, respectively) and those with the highest abundance of particular species.

Trophic Groups, Families, and Species

Biomass and abundance were distributed unevenly throughout trophic and taxonomic groups. The most abundant trophic groups in terms of biomass and abundance were herbivores (H, e.g., parrotfish, damselfish) and invertivores (I, e.g., grunts, butterflyfishes), while piscivores (P, e.g., snappers, groupers) constituted a

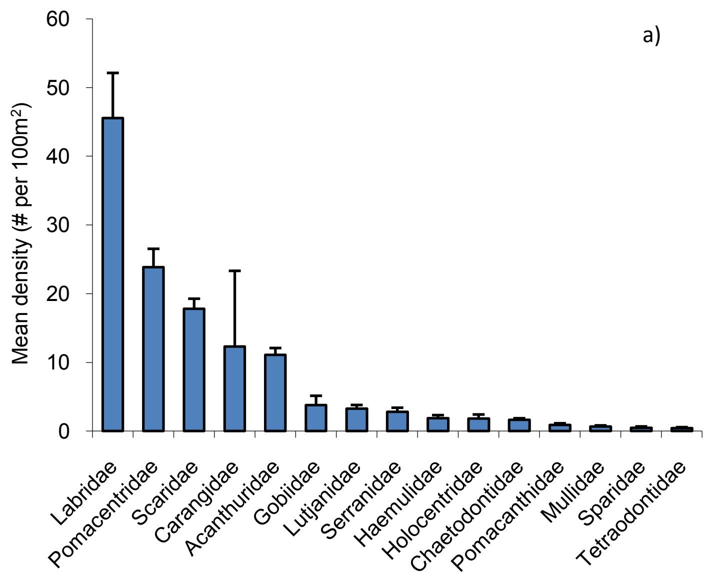


Figure 3.27. Mean (± SE) a) density and b) biomass of fish families observed in Vieques survey.

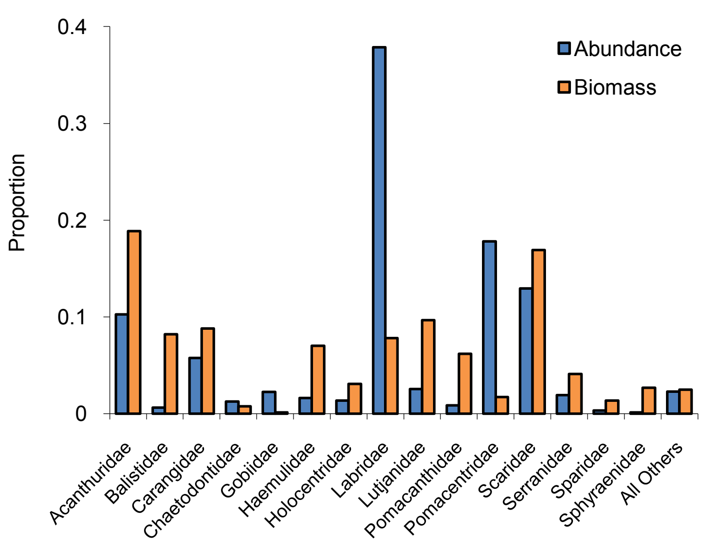


Figure 3.28. Proportional distribution of abundance and biomass of major fish families.

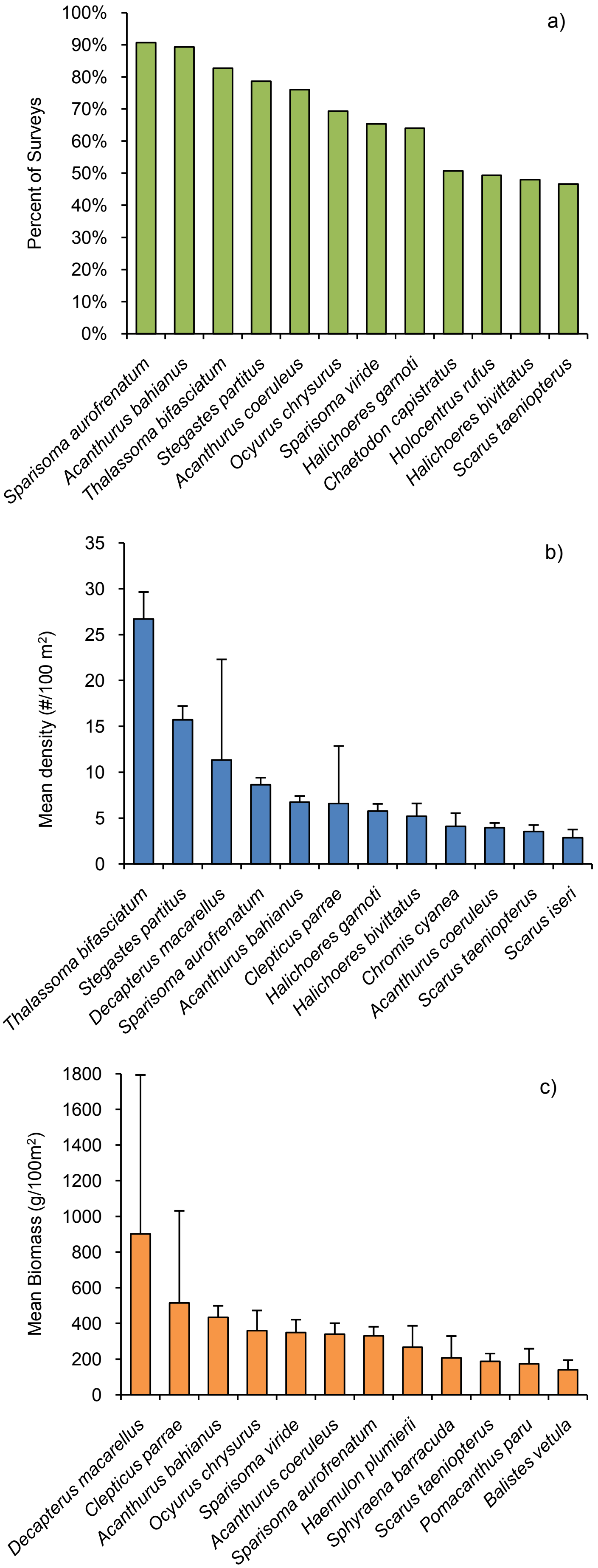


Figure 3.29. Top twelve fish species by a) survey frequency, b) mean (± SE) density, and c) mean (± SE) biomass.

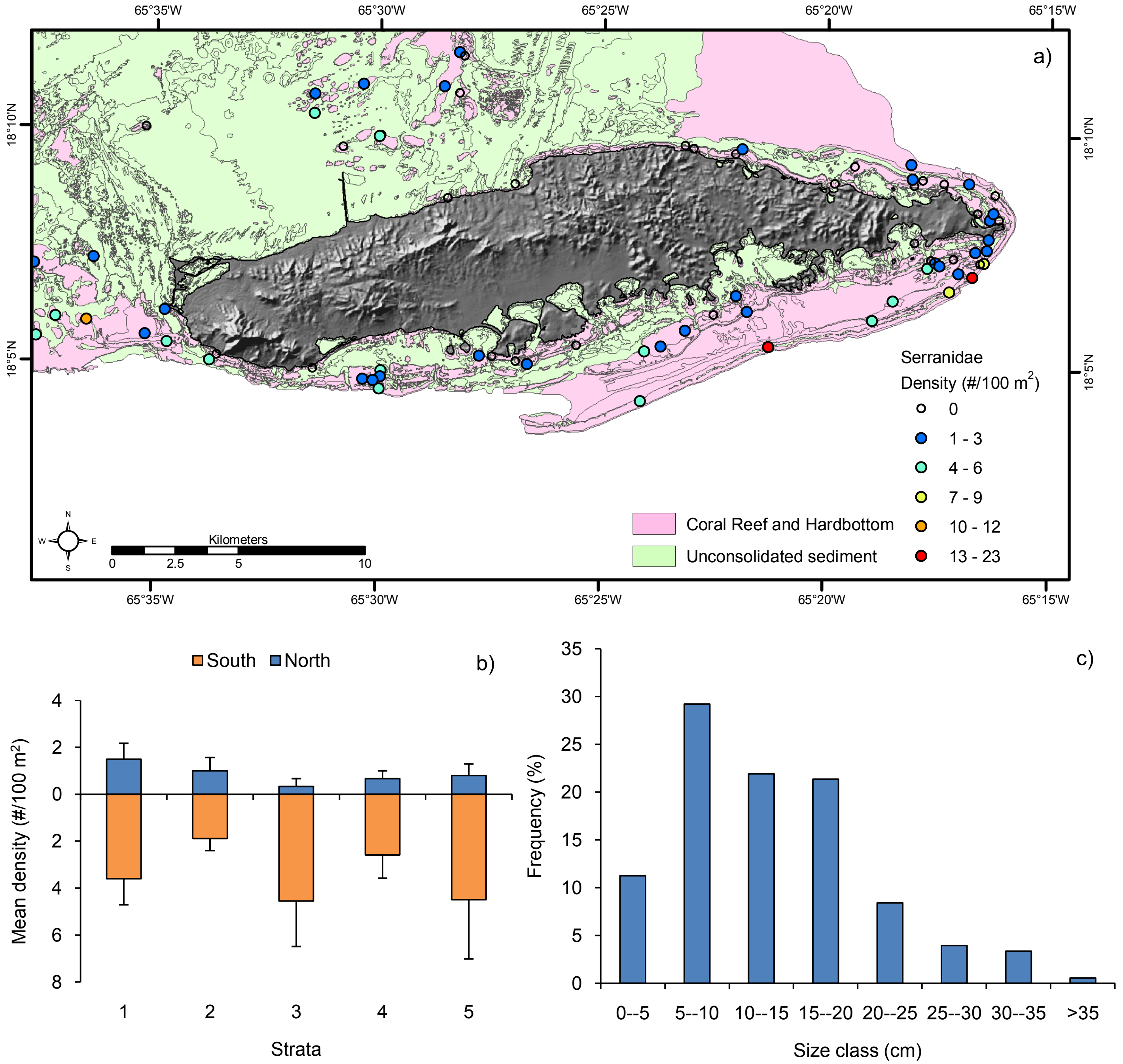


Figure 3.30. a) Spatial distribution, b) mean (±SE) density across strata, and c) size class frequency histogram of groupers, hamlets and seabasses (Family Serranidae).

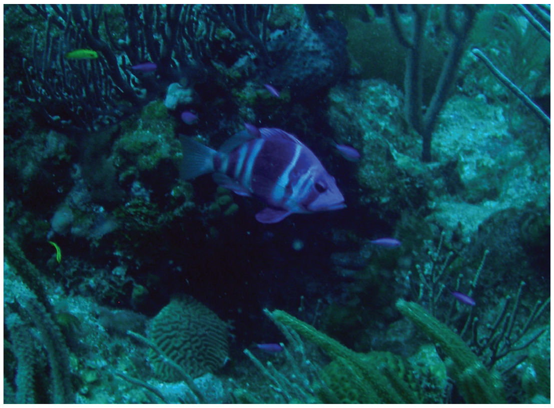


Image 3.7. Indigo hamlet (*Hypoplectrus indigo*). Photo: CCMA Biogeography Branch.

smaller percentage (Figure 3.25). The proportional biomass of each trophic group was generally similar across strata, with the exception of 1-South, where the zooplanktivore (Z) *D. marcarellus* accounted for a high proportion of the total biomass (Figure 3.26) due to the one large school. In addition, herbivores tended to constitute a slightly greater proportion of the total biomass in the easternmost strata in comparison to the western counterparts. Piscivores accounted for approximately one-third of the biomass in 4-North, but this was primarily due to one nurse shark (*Ginglymostoma cirratum*) present in one survey.

Families with the highest mean abundance and biomass are ranked in Figure 3.27a-b and by their proportional abundance/biomass in Figure 3.28. Approximately 90% of individuals and biomass came from 7 and 10 families, respectively. While individuals

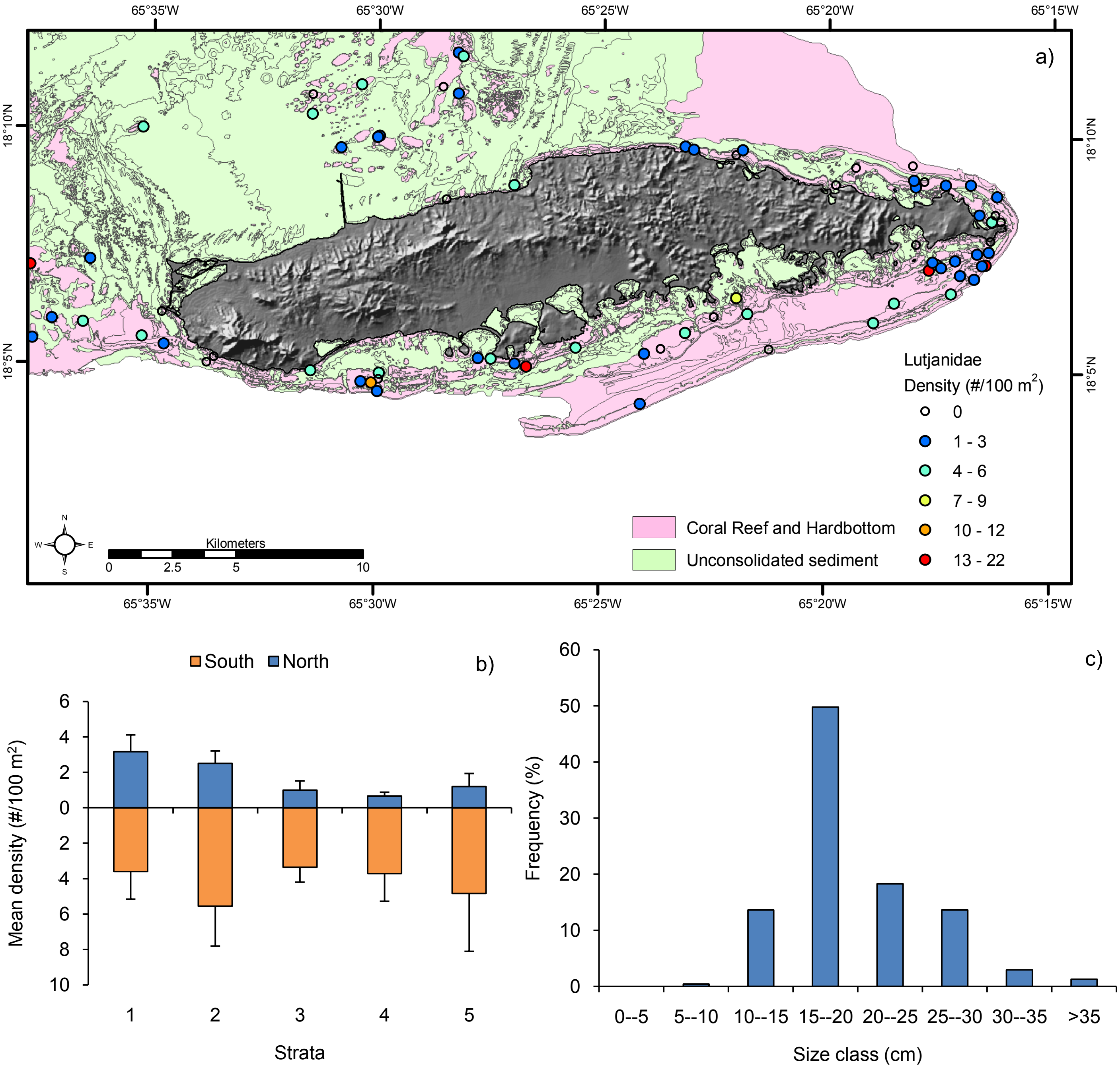


Figure 3.31. a) Spatial distribution, b) mean (±SE) density across strata, and c) size class frequency histogram of snappers (Family Lutjanidae).

from the families Labridae (wrasses) and Pomacentridae (damselfishes) were the most numerically abundant, surgeonfishes (Family Acanthuridae) and parrotfishes (Family Scaridae) accounted for the highest proportion of biomass (Figure 2.28).

The most frequently observed fish species include the redband parrotfish (*Sparisoma aurofrenatum*), ocean surgeonfish (*Acanthurus bahianus*), bluehead (*Thalassia bifasciatum*), bicolor damselfish (*Stegastes partitus*), and blue tang (*Acanthurus coeruleus*), which were all sighted at over 70% of the transects (Figure 3.29a). These species also ranked high in terms of mean abundance, and with the exception of the small bodied *S. partitus*, biomass (Figure 3.29b-c). Other species such as *D. marcarellus* and *Clepticus parrae* (creole wrasse) were not frequently sighted, but were patchily abundant when found. Aside from the one *G. cirratum*, no other sharks were observed in any of the transects.

Summary information on the spatial distribution, mean density by strata, and size frequency for select families and species are displayed in Figures 3.30-3.33 and Figures 3.34-3.43, respectively.

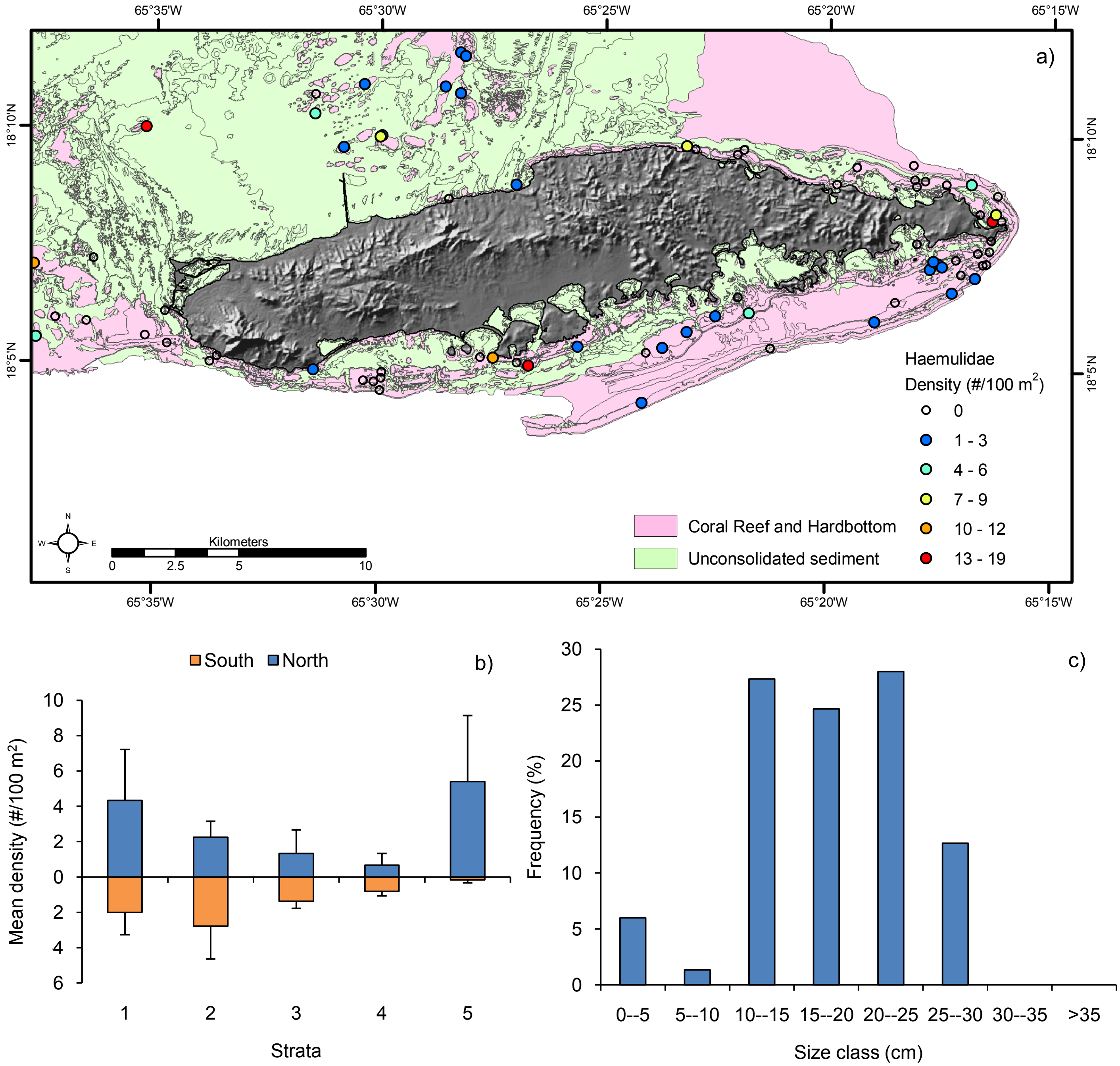


Figure 3.32. a) Spatial distribution, b) mean (±SE) density across strata, and c) size class frequency histogram of grunts (Family Haemulidae).

Serranids (groupers, hamlets and seabasses) were observed in 63% of the survey transects, with higher densities on the south side of the island (Figure 3.30). The family was represented by 15 species, with red hind (*Epinephelus guttatus*), harlequin bass (*Serranus tigrinus*), and coney (*Cephalopholis fulva*) most frequently sighted. Size frequency was skewed towards the smaller size classes, with few large adults observed. The commercially important tiger grouper was only observed at one survey location in the southwestern portion of the study area.

Fishes of the family Lutjanidae (snappers) were observed at 75% of the survey locations. Again, sighting frequency and density tended to be higher in the southern strata (Figure 3.31). Seven Lutjanid species were documented, with the yellowtail snapper (*Ocyurus chrysurus*) accounting for the majority of the sightings, followed by schoolmaster (*Lutjanus apodus*). The remaining species were infrequently observed.

Grunts (Family Haemulidae) were present within 44% of survey transects. Distribution tended to be patchy and at most sites only a few individuals were observed (Figure 3.32). Sites with higher densities were located on

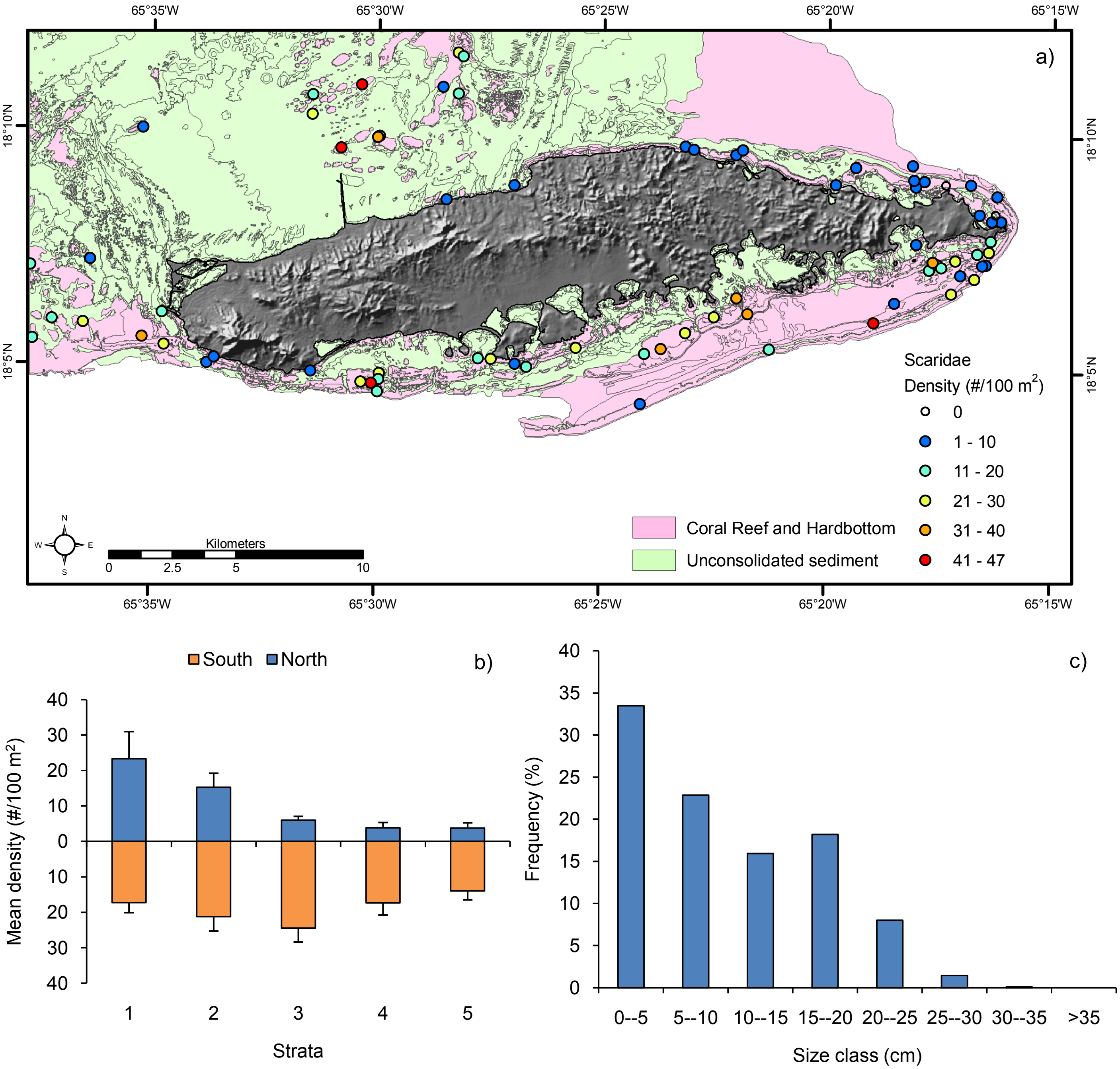
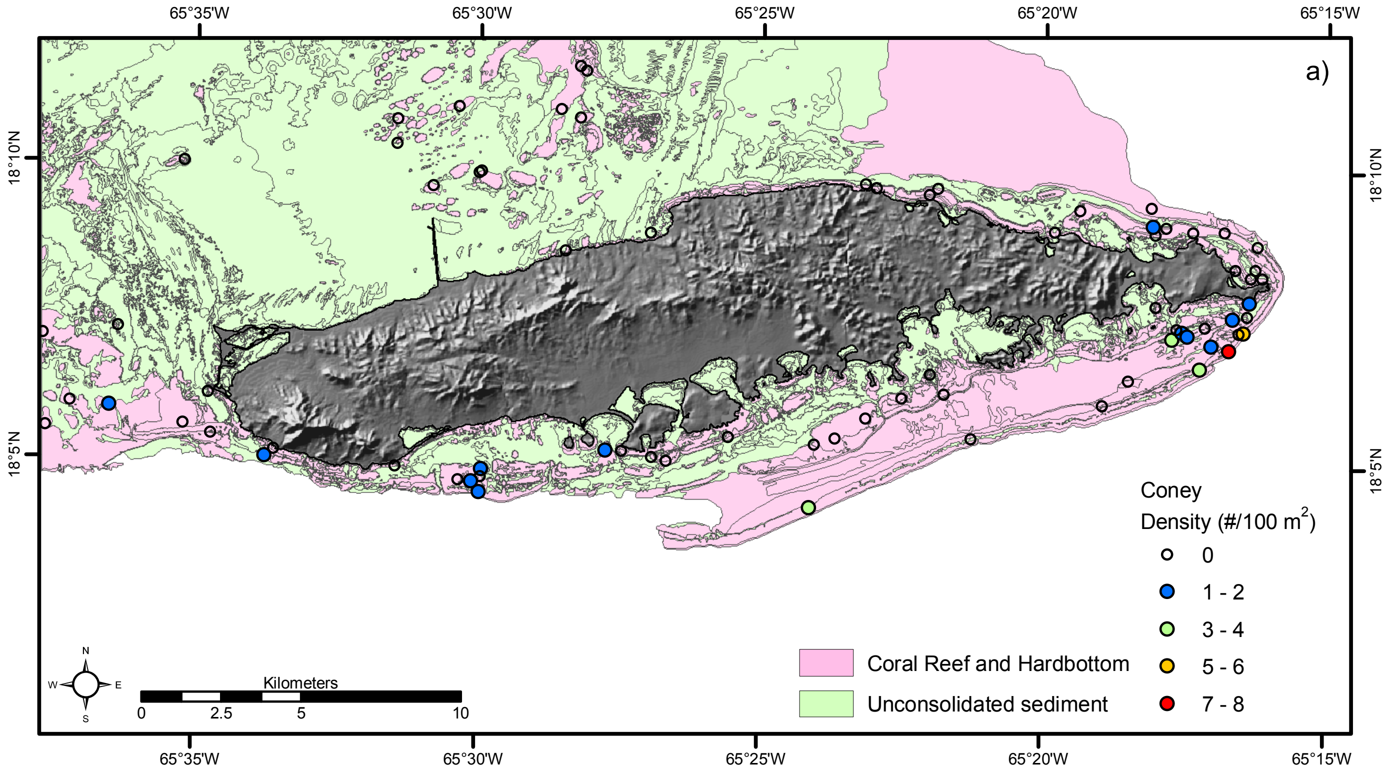


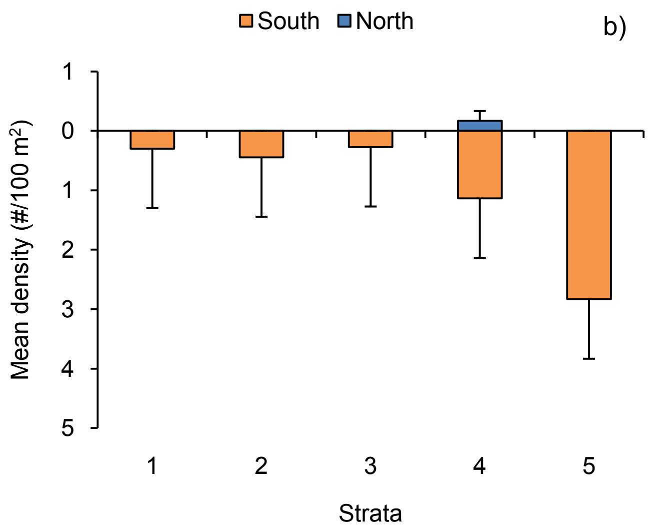
Figure 3.33. a) Spatial distribution, b) mean (±SE) density across strata, and c) size class frequency histogram of parrotfishes (Family Scaridae).

the northeast tip, on patch reefs in the northwest area, and south of Ensenada Sombe and Puerto Mosquito. Of the eight species observed, French grunt (*Haemulon flavolineatum*) and white grunt (*Haemulon plumierii*) were most frequently sighted and had the highest mean abundance and biomass.

Parrotfishes (Family Scaridae) were common members of the Vieques reef community, occurring in all but two of the survey transects. However, they were less abundant in the northeastern strata compared to the rest of the island (Figure 3.33). Of the seven species, the redband parrotfish (*Sparisoma aurofrenatum*) and princess parrotfish (*Scarus taeniopterus*) were most abundant, while the stoplight parrotfish (*Sparisoma viride*) had the highest mean biomass.

Coney (*C. fulva*) demonstrated one of the most distinct spatial patterns of any species considered and were located almost exclusively on the south side of Vieques, with the highest densities in the southeastern strata (Figure 3.34). Fish were most frequently associated with aggregate reef and pavement structure types, and to a lesser extent sand w/ scattered coral and rock. The majority of observed individuals were small adults, with fewer juveniles or large adults.





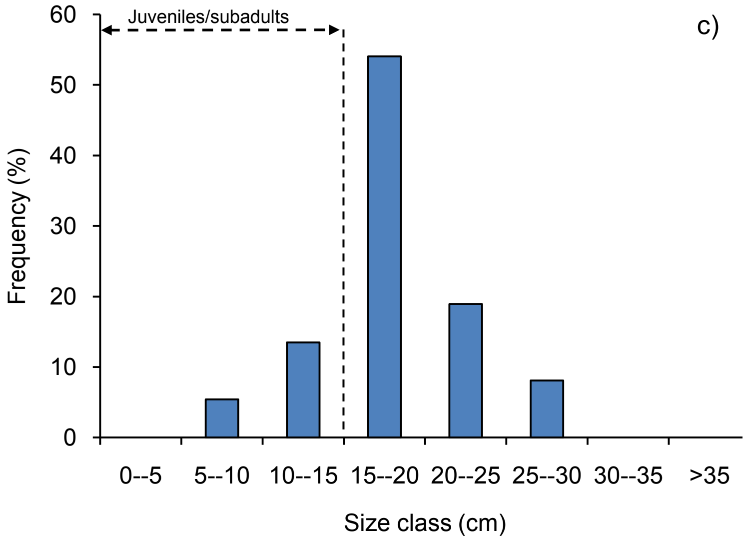


Figure 3.34. a) Spatial distribution, b) mean (±SE) density across strata, and c) size class frequency histogram of coney (*Cephalopholis fulva*).

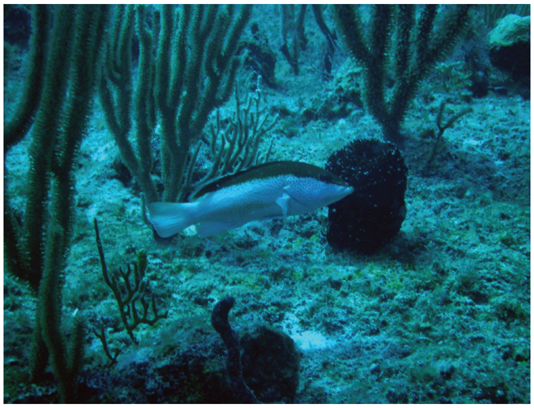


Image 3.8. Coney (*Cephalopholis fulva*). Photo: CCMA Biogeography Branch.

Red hind (*E. guttatus*) were sighted in 29% of survey transects, more frequently in southern strata and generally in low densities (Figure 3.35). Individuals were found across all hardbottom types. The majority of individuals were juveniles/subadults and small adults. The largest red hind observed were within the 30-35 cm size class, whereas the maximum known size for this species is 76 cm total length (Fishbase, Freose and Pauly 2008).

Schoolmaster (*L. apodus*) were infrequently observed (12 of survey transects) and generally in low densities (Figure 3.36). The large mean abundance in 2-South was due to one location where 20 individuals were recorded. This site with large schoolmaster density was found on pavement habitat type, but the species was found across all hardbottom types. The majority of individuals were juveniles/subadults and small adults.

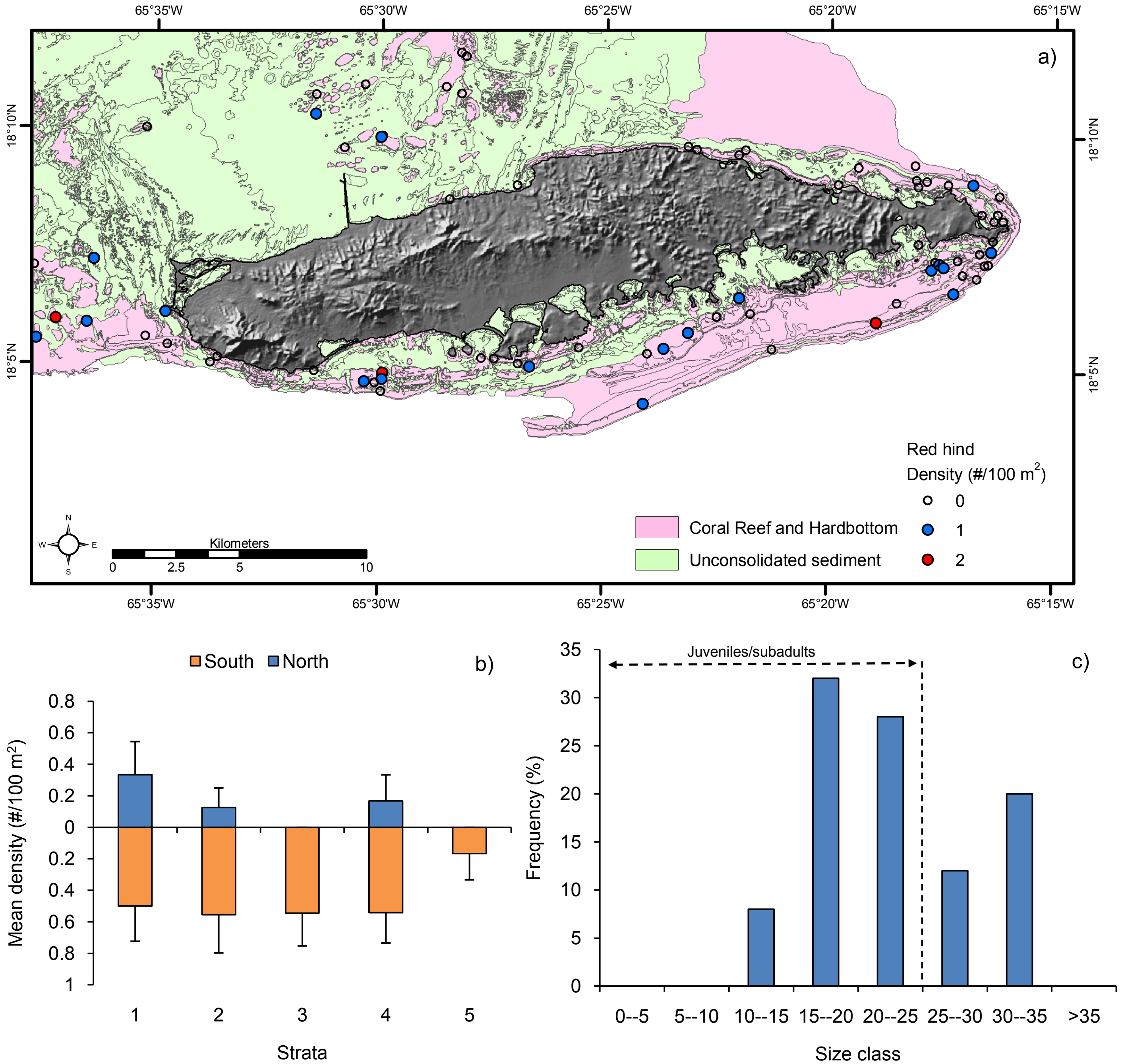


Figure 3.35. a) Spatial distribution, b) mean (±SE) density across strata, and c) size class frequency histogram of red hind (*Epinephelus guttatus*).

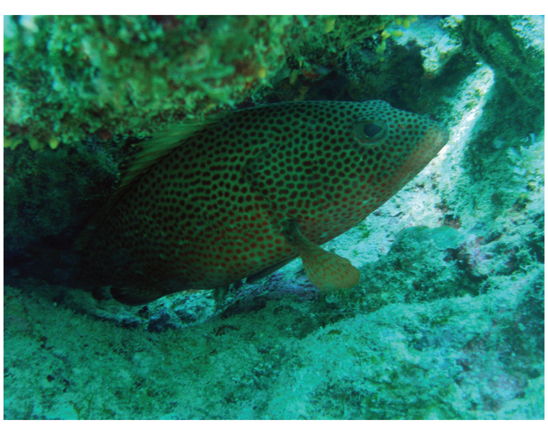
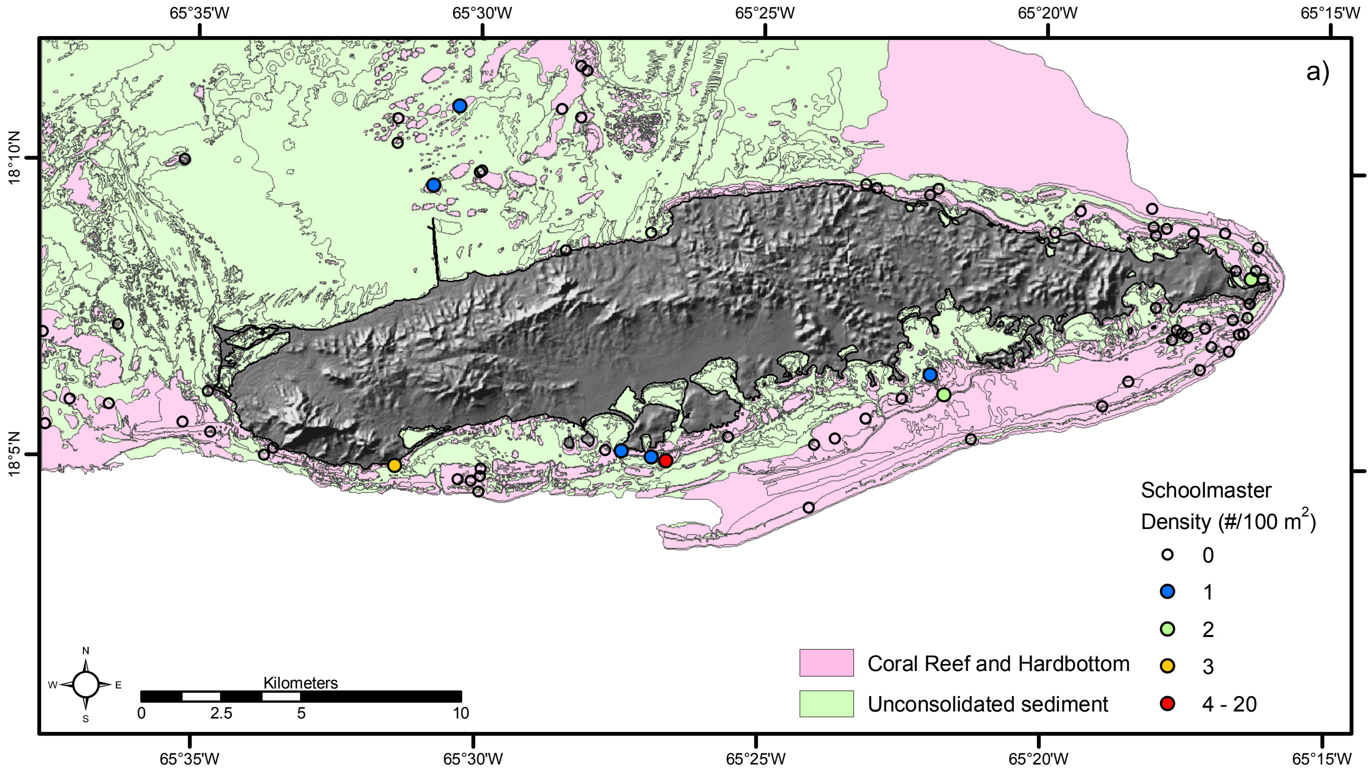
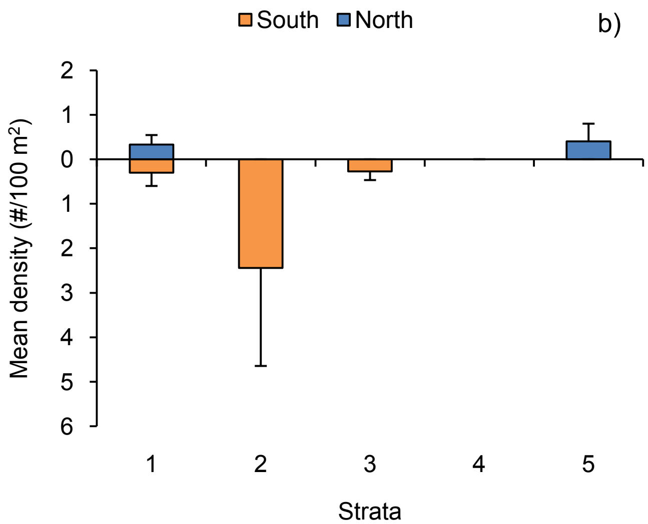


Image 3.9. Red hind (*Epinephelus guttatus*). Photo: CCMA Biogeography Branch.

The most abundant lutjanid species, yellowtail snapper (*O.chrysurus*) were observed in 69% of the survey transects (Figure 3.37). The species was found all around the island and across all hardbottom types, but higher densities generally occurred on the south side. The two sites with the highest density occurred at the far eastern and western edges of the survey area. The majority of the individuals were in the juvenile/subadult size classes; only a small percentage of yellowtail snapper were adult-sized.

French grunt (*H. flavolineatum*) were present at 25% of the survey sites and were largely absent from sites on the northwestern portion of the island (Figure 3.38). Sites with the highest densities were located on the northeastern tip and in strata 2-South. The majority of the individuals were larger juveniles/subadults and small adults, whereas few small juveniles or large adults were ob-





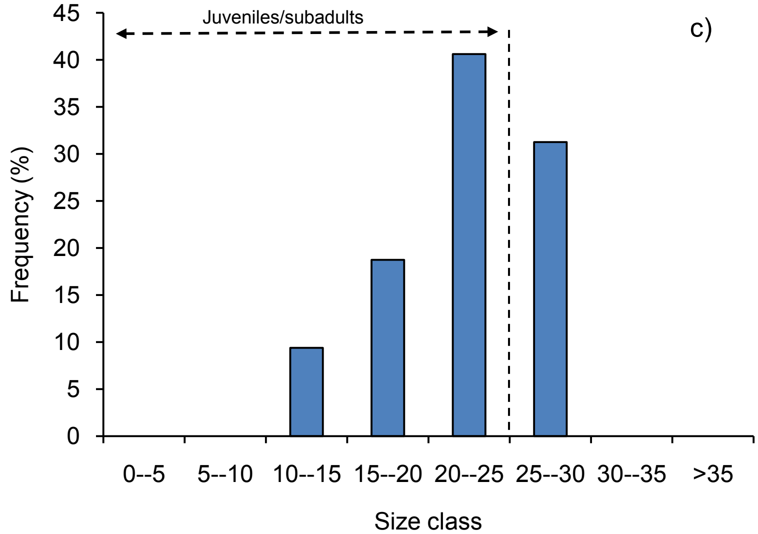


Figure 3.36. a) Spatial distribution, b) mean (±SE) density across strata, and c) size class frequency histogram of schoolmaster (*Lutjanus apodus*).

served. The species was found most frequently on aggregate reef, pavement, and pavement with sand channels habitat.

Hogfish (*L. maximus*) were present in only 12% of the survey transects but exhibited a very spatially distinct distribution pattern. The species were largely associated with patch reefs on the north/northwest portion of the survey area (Figure 3.39). Only one individual was observed in survey transects on the south side of the island. Individuals were primarily juveniles/subadults and small adults. Two large hoghfish of 55 cm were also observed.

Ocean surgeonfish (*A. bahianus*) were sighted in 89% of the surveys and were present in all areas on all hardbottom types (Figure 3.40). Mean density was highest in 5-South and lowest in 1-South. Subadults and small adults were most frequent, while small juveniles comprised a smaller percentage of the sightings.

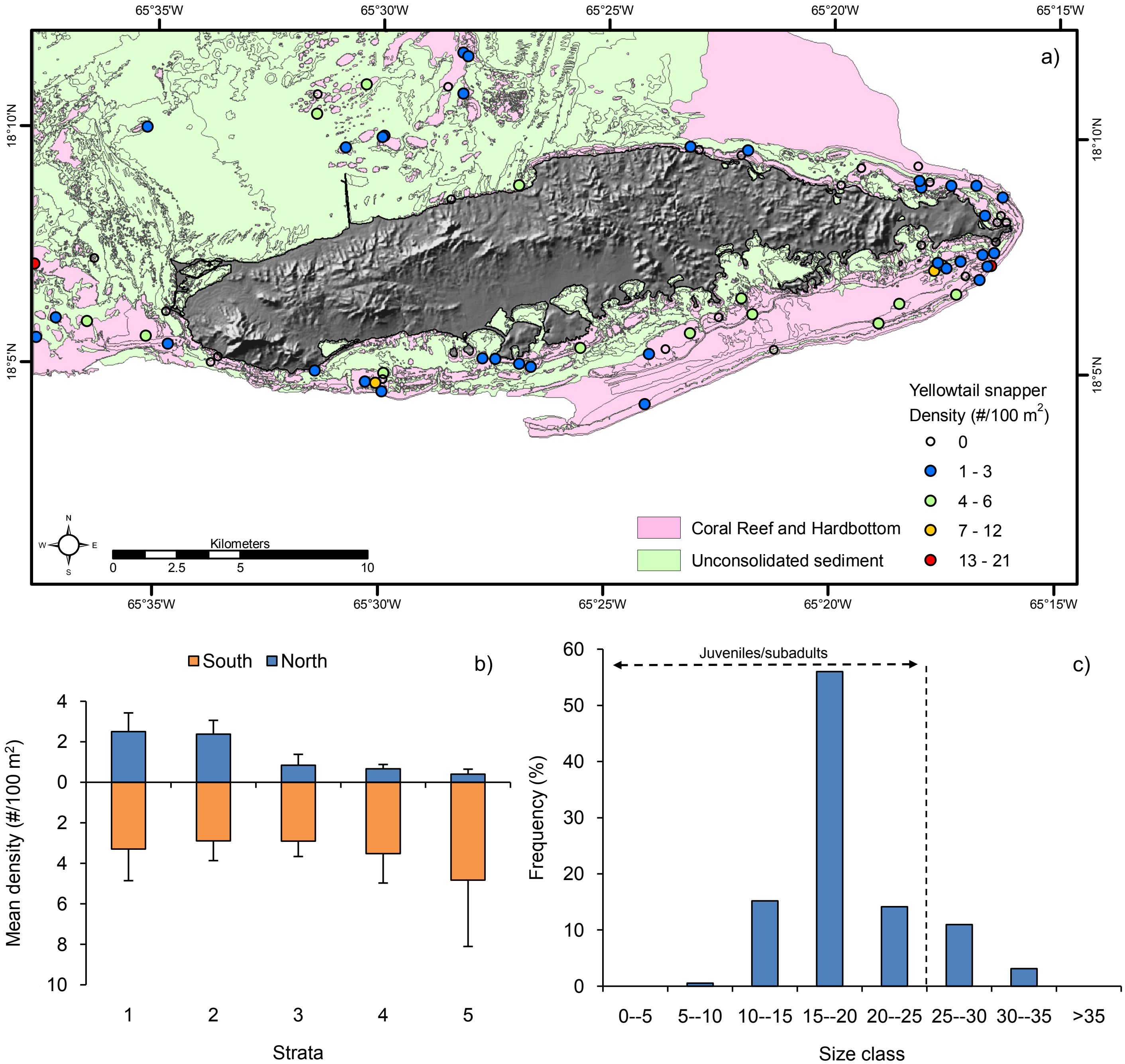


Figure 3.37. a) Spatial distribution, b) mean (±SE) density across strata, and c) size class frequency histogram of yellowtail snapper (*Ocyurus chrysurus*).

Blue tang (*A. coeruleus*) were present in 76% of survey transects and were associated with all hardbottom types (Figure 3.41). While there were no clear spatial patterns, density tended to be higher at patch reefs on the north shore, on the eastern tip, and on fringing reefs on the south shore. The species exhibited a peak in frequency for small adults.

Redband parrotfish (*S. aurofrenatum*) was the most frequently sighted fish and was present in 91% of the transects (Figure 3.42). With the exception of 1-North, mean density was higher in all southern strata compared to the north. Sites from which the species was absent were all located in strata 3-, 4-, and 5-North. Approximately two-thirds of all observed individuals were juveniles/subadults.

Stoplight parrotfish (*S. viride*) were sighted in 65% of the survey transects (Figure 3.43). Although the species was associated with all hardbottom types, many of the sites with the highest densities were located in structure types of higher complexity (e.g., patch reefs, aggregate reef, pavement w/ sand channels). In particular, mean density in 1- and 2-North was high due to large densities on several patch reefs.

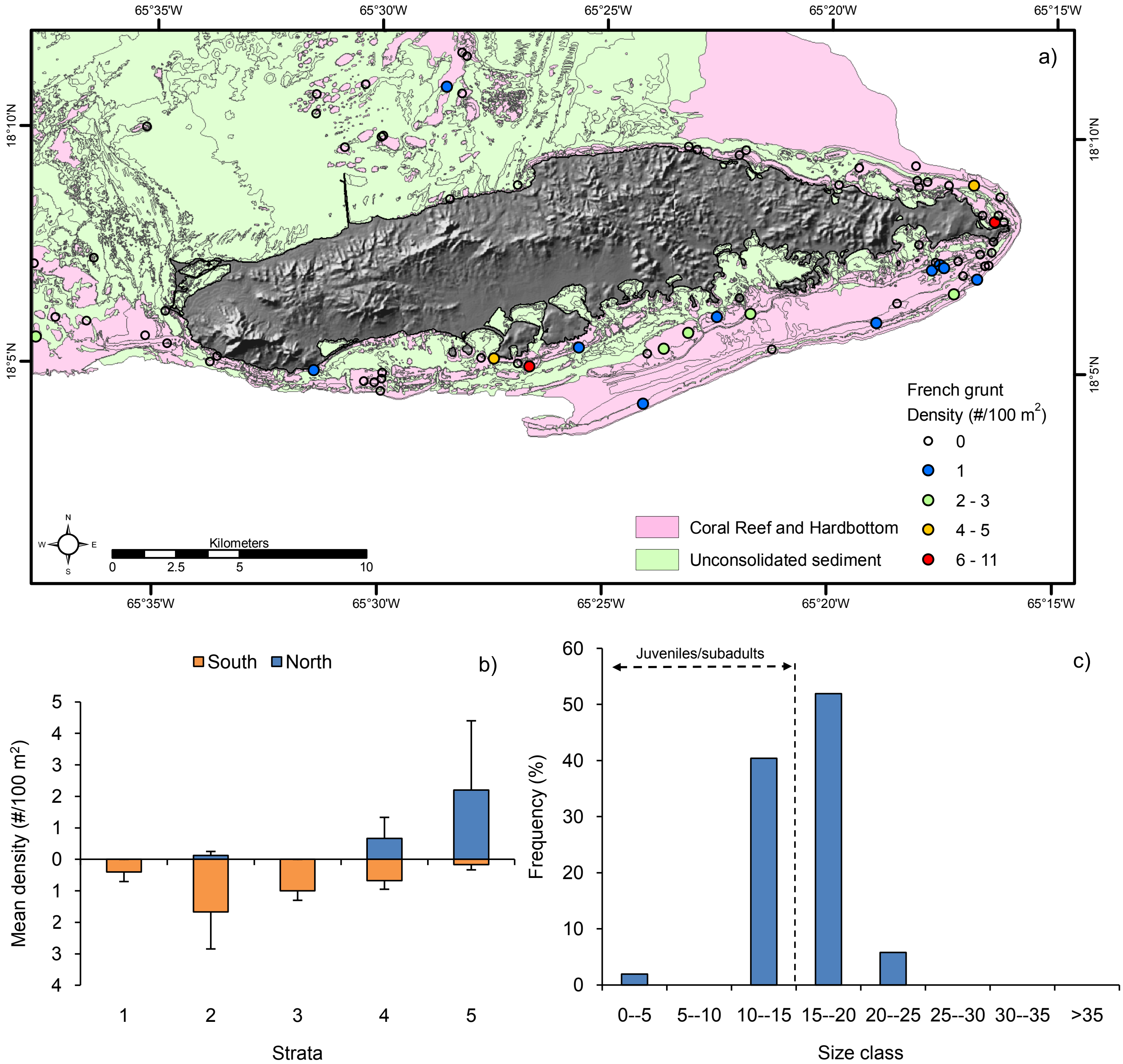


Figure 3.38. a) Spatial distribution, b) mean (±SE) density across strata, and c) size class frequency histogram of french grunt (*Haemulon flavolineatum*).

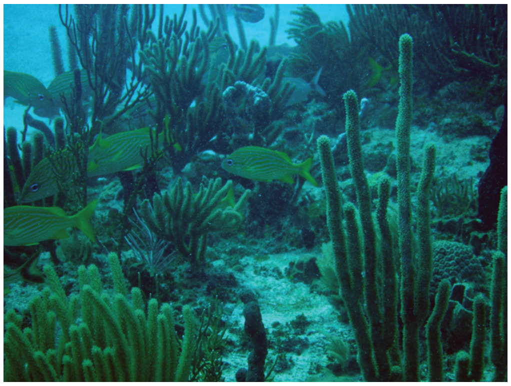


Image 3.10. French grunt (*Haemulon flavolineatum*). Photo: CCMA Biogeography Branch.

Due to differences in site selection, location and survey methods, it is not possible to make direct comparisons in metrics from this survey with those from previous studies. However, in terms of relative abundance, the fish species composition observed here was comparable with rankings from several earlier assessments (Table 3.5). *T. bifasciatum* was the most abundant species in two other surveys (DON 1979; GMI 2003) and ranked among the top five most abundant in the remaining studies. Of the ten most abundant species in this study, six were also shared with GMI (2003). The masked goby (*Coryphopterus personatus*) was the most abundant species in Garcia-Sais et al. (2001, 2004) but was only the 19th most abundant here and occurred in only 4% of transects. However, this species tends to occur in aggregations, and hence can be locally abundant when present.

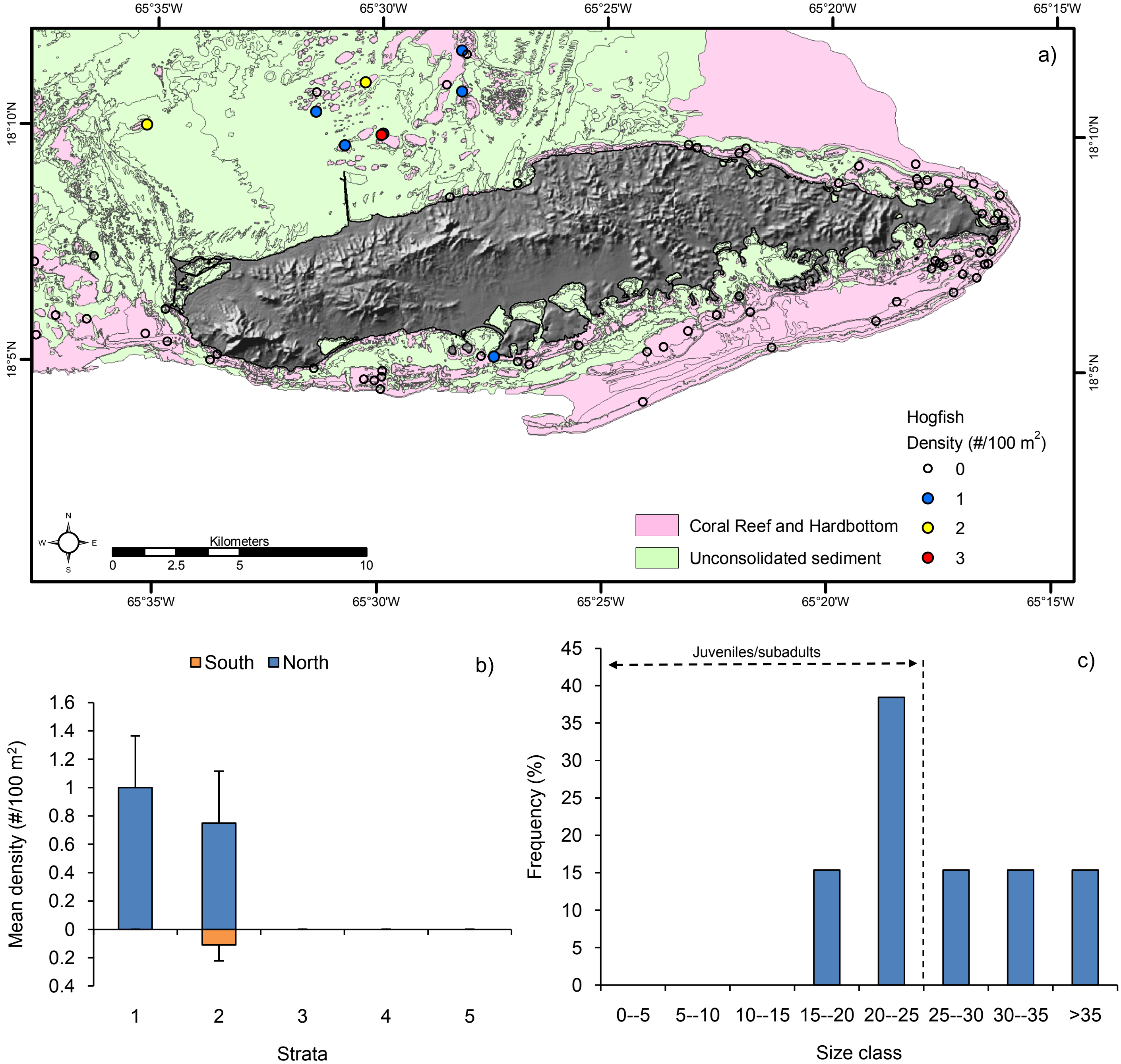


Figure 3.39. a) Spatial distribution, b) mean (±SE) density across strata, and c) size class frequency histogram of hogfish (*Lachnolaimus maximus*).

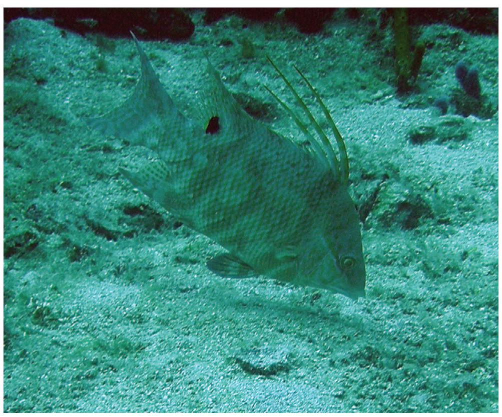


Image 3.11. Hogfish (*Lachnolaimus maximus*).
Photo: CCMA Biogeography Branch.

These studies also reported heterogeneity in fish communities within/among benthic habitat types and at regional scales, although findings among studies were inconsistent. While DON (1986) reported communities to be similar across locations, GMI (2003) also detected a difference in fish communities between sites located north and south of the island using MDS analysis. Although their study area was restricted to the eastern military area (i.e., overlapped with Strata 3 and 4 of this study area), the MDS results were similar in that southern sites tended to be more clustered together, while the northern samples were more dissimilar.

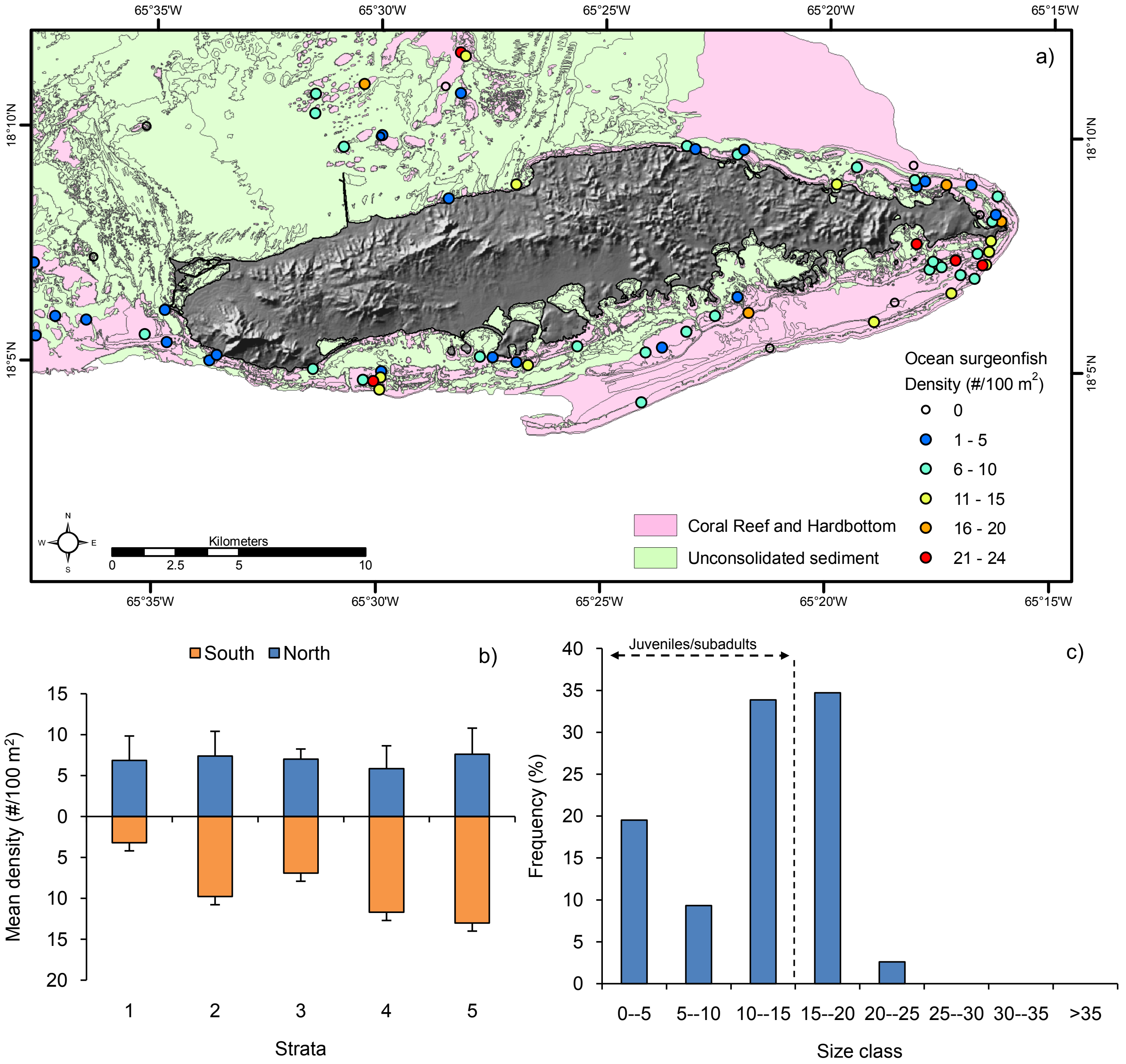


Figure 3.40. a) Spatial distribution, b) mean (±SE) density across strata, and c) size class frequency histogram of ocean surgeonfish (*Acanthurus bahianus*).

Image 3.12. Ocean surgeonfish (*Acanthurus bahianus*). Photo: CCMA Biogeography Branch.

Comparison with other U.S. Caribbean monitoring locations

To put our results in context with nearby study areas in the U.S. Caribbean, fish data from the 2007 Vieques survey were compared with three locations (La Parguera in southwestern Puerto Rico, St. Croix and St. John, USVI) that have been monitored by the Biogeography Branch using identical methods. Data were summarized for the three locations from 2003-2007. Only hardbottom sites were included for a total number of sites from each location as follows: SW Puerto Rico (450), St. Croix (714), and St. John (617).

Several fish community metrics (species richness, density, biomass) were compared among the four locations. Density and biomass data were not normally distributed and richness data did not meet the assumption of homogeneity of variances, therefore non-parametric Wil-

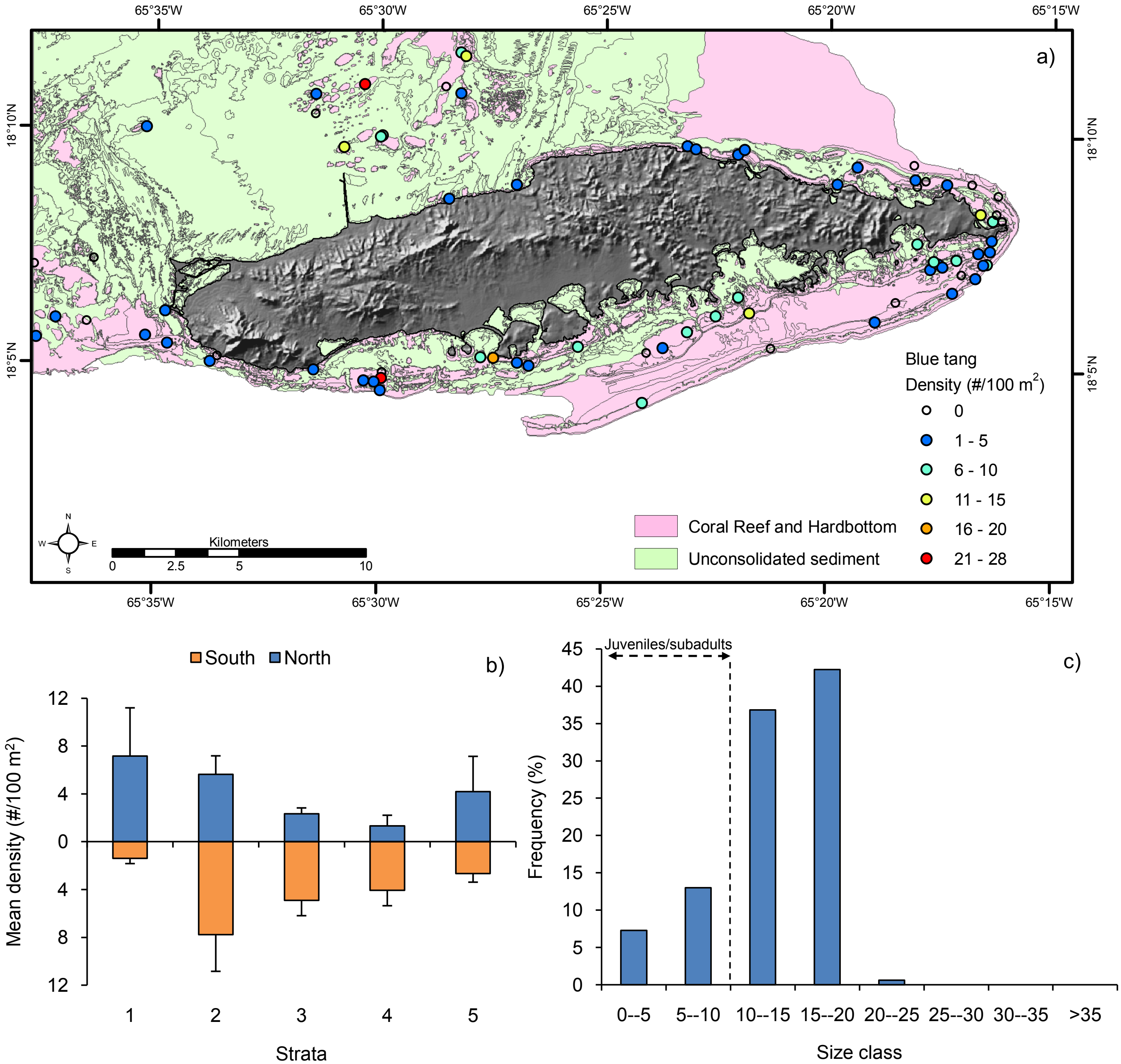


Figure 3.41. a) Spatial distribution, b) mean (±SE) density across strata, and c) size class frequency histogram of blue tang (*Acanthurus coeruleus*).

coxon tests and the corresponding non-parametric Dunn's test (Zar 1999) were used to test for differences among regions.

Species richness, density, and biomass were significantly greater in St. John ($p<0.05$) than each of the three other study locations (Figure 3.44a-c). Richness was similar among Vieques, SW Puerto Rico, and St. Croix and averaged 18-19 species/100 m^2). Fish density was also significantly greater in St. Croix in comparison to Vieques and SW Puerto Rico, and in Vieques compared to SW Puerto Rico. While biomass was significantly greater in St. Croix than SW Puerto Rico, there were no differences between Vieques and either St. Croix or SW Puerto Rico.

Abundance and biomass of key families were not always consistent across regions (Figure 3.45). Both abundance and biomass of snappers (Lutjanidae) were significantly greater in Vieques compared to each of the other study regions ($p<0.001$). In contrast, scarid abundance was significantly lower in Vieques compared to St. John and SW Puerto Rico, and biomass was significantly lower than in St. John. Serranid abundance and

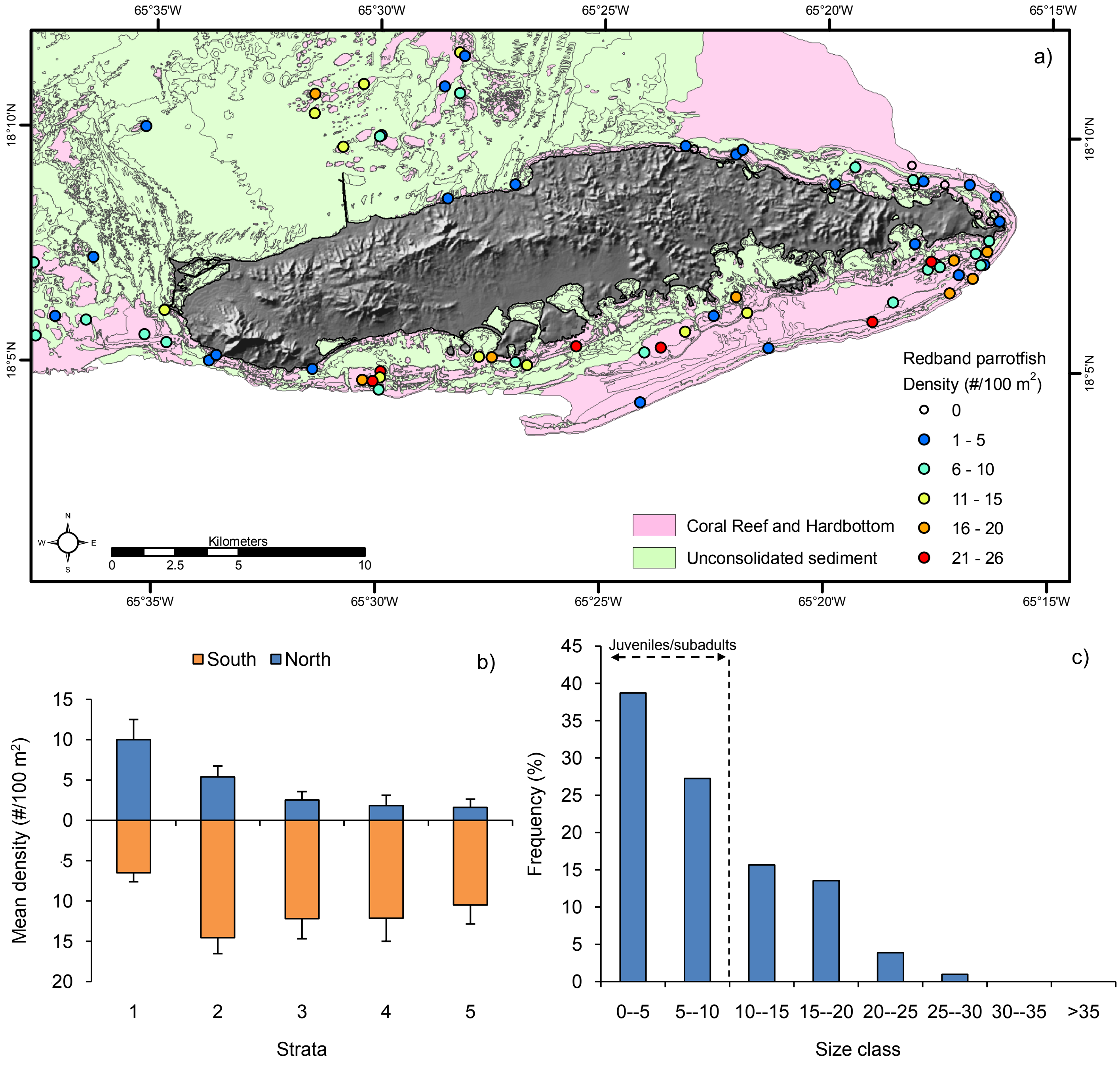


Figure 3.42. a) Spatial distribution, b) mean (±SE) density across strata, and c) size class frequency histogram of redband parrotfish (*Sparisoma aurofrenatum*).

biomass were significantly lower in Vieques than St. Croix and St. John, but biomass was significantly greater than in SW Puerto Rico. There were no significant differences in abundance or biomass of grunts (Haemulidae) across regions.

Macroinvertebrates

Diadema antillarum was observed at seven of 75 sites for a total of 106 individuals. Five out of seven sites were located on the north side, while the site with the highest observed density (54 urchins/100 m^2), was located in 4-South (Figure 3.46).

One immature *S. gigas* was observed in a survey transect on sand w/ scattered coral and rock habitat. The absence of queen conch in this survey is expected as they are typically associated with softbottom.

No spiny lobster (*P. argus*) were recorded during the survey, despite surveying 7500 m^2 of hardbottom.

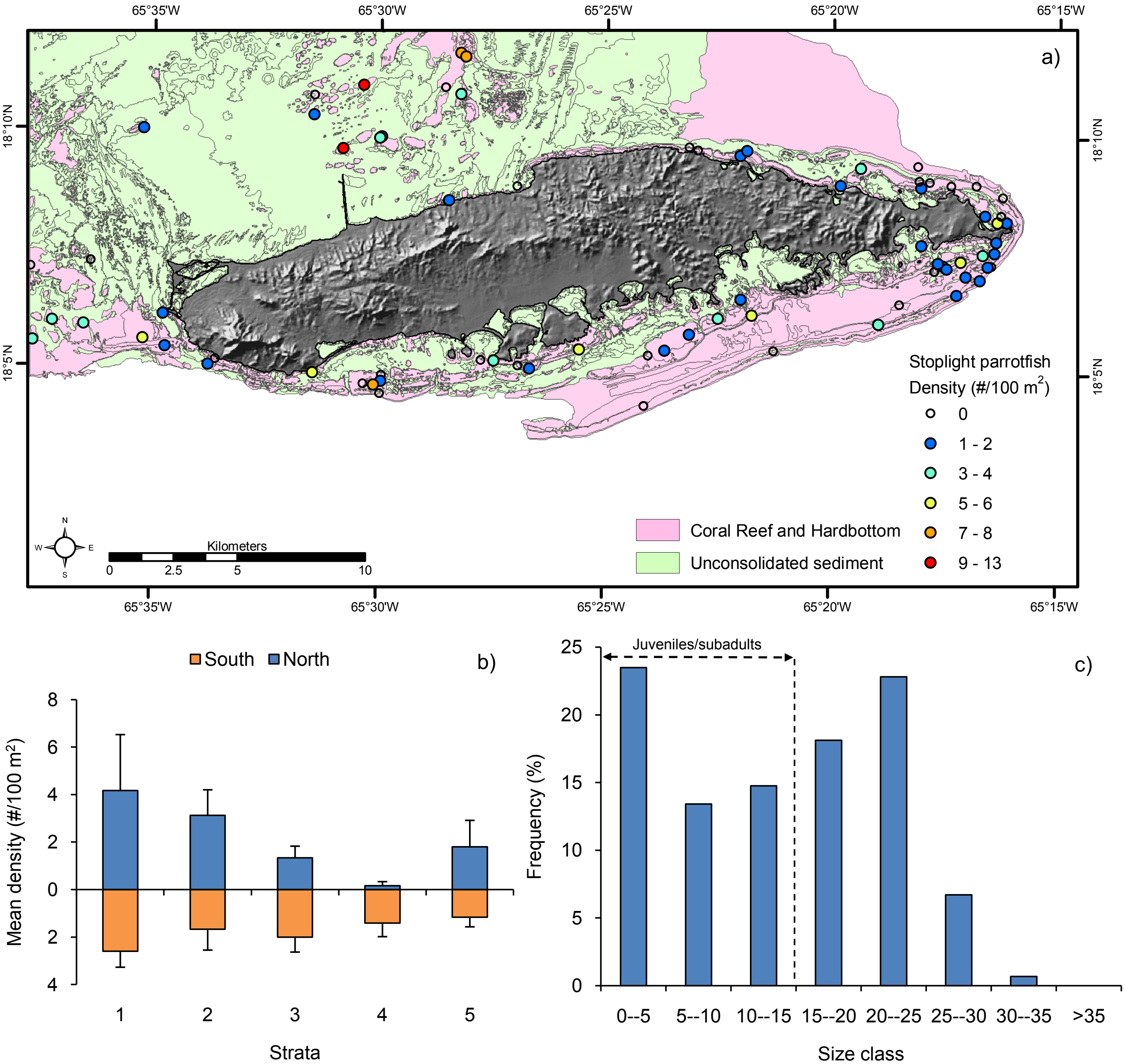


Figure 3.43. a) Spatial distribution, b) mean (±SE) density across strata, and c) size class frequency histogram of stoplight parrotfish (*Sparisoma viride*).

Marine Debris

A total of sixteen debris items, all unexploded ordnance, were found within the survey transect at three locations (Figure 3.47). All three sites were located on the north side of the island offshore of former Navy areas. The largest observed munition was an MK-81 250 lb bomb of approximately 150 cm in length. The site with the highest density of ordnance (13 items/100m²) was located west of the Live Impact Area, but was still located within the area of special concern. Four of the items appeared to be intact ordnance (~40x8 cm) while the remaining items were smaller and may have been fragments of larger items. Munitions were observed outside survey transects at five additional locations. Although no obvious impacts to the habitat were observed, ordnance was often integrated into the surrounding substrate and colonized by organisms such as turf algae, macroalgae, crustose algae, and encrusting sponge. Preliminary identification of items was made when possible (Dave Green, PIKA, personal communication) and provided to the Navy for their records.

Table 3.5. Abundance ranks of the ten most abundant reef fish species among reef/hardbottom in the present study and five previous studies.

Ranking	Present study	DON 1979	DON 1986	Garcia-Sais et al. 2001	GMI 2003	Garcia-Sais et al. 2004
1	*Thalassoma bifasciatum*	*Thalassoma bifasciatum*	*Acanthurus coeruleus*	*Coryphopterus personatus*	*Thalassoma bifasciatum*	*Coryphopterus personatus*
2	*Stegastes partitus*	*Acanthurus coeruleus*	*Sparisoma viride*	*Stegastes partitus*	*Stegastes partitus*	*Clepticus parrae*
3	*Decapterus macarellus*	*Acanthurus chirurgus*	*Sparisoma rubripinne*	*Stegastes planifrons*	*Chromis multilineata*	*Chromis cyanea*
4	*Sparisoma aurofrenatum*	*Ophioblennius atlanticus*	*Thalassoma bifasciatum*	*Scarus iseri*	*Acanthurus bahianus*	*Thalassoma bifasciatum*
5	*Acanthurus bahianus*	*Acanthurus bahianus*	*Acanthurus chirurgus*	*Thalassoma bifasciatum*	*Acanthurus coeruleus*	*Inermia vittata*
6	*Clepticus parrae*	*Abudefduf saxatilis*	*Scarus iseri*	*Chromis multilineata*	*Halichoeres bivittatus*	*Scarus iseri*
7	*Halichoeres garnoti*	*Stegastes adustus*	*Scarus taeniopterus*	*Stegastes adustus*	*Sparisoma aurofrenatum*	*Stegastes adustus*
8	*Halichoeres bivittatus*	*Chromis multilineata*	*Haemulon flavolineatum*	*Decapterus macarellus*	*Halichoeres maculipinna*	*Stegastes partitus*
9	*Chromis cyanea*	*Scarus iseri*	*Holocentrus adscensionis*	*Chromis cyanea*	*Scarus iseri*	*Gobiosoma evelynae*
10	*Acanthurus coeruleus*	*Scarus taeniopterus*	*Sparisoma aurofrenatum*	*Haemulon flavolineatum*	*Stegastes adustus*	*Sparisoma viride*

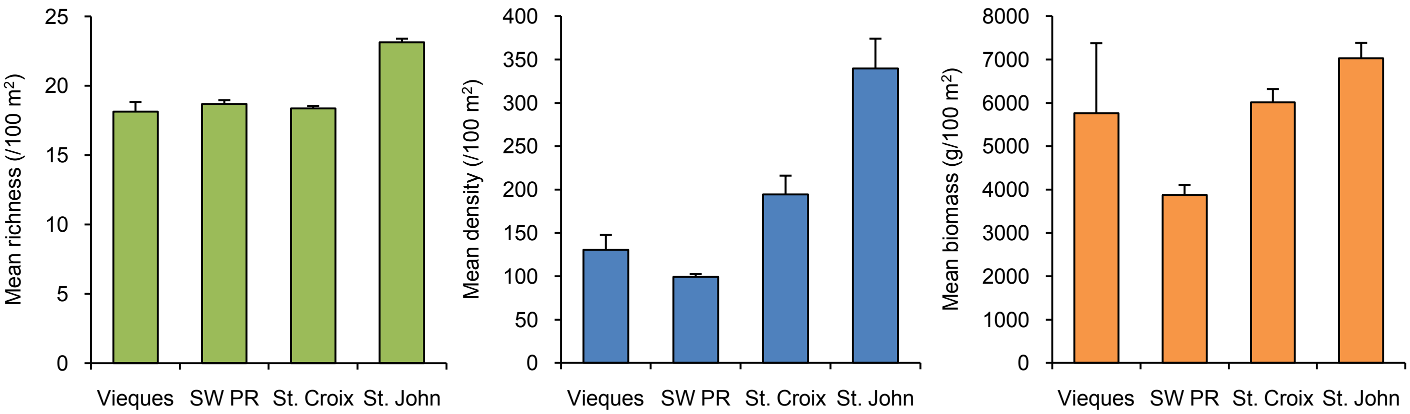


Figure 3.44. Estimated mean (±SE) fish species richness, density, and biomass at Vieques in May 2007 and other CCMA Biogeography Branch Caribbean monitoring locations (2003-2007): La Parguera in SW Puerto Rico (n=450), St. Croix (n=714) and St. John (n=617). See Figure 3.16a for map of the study areas.

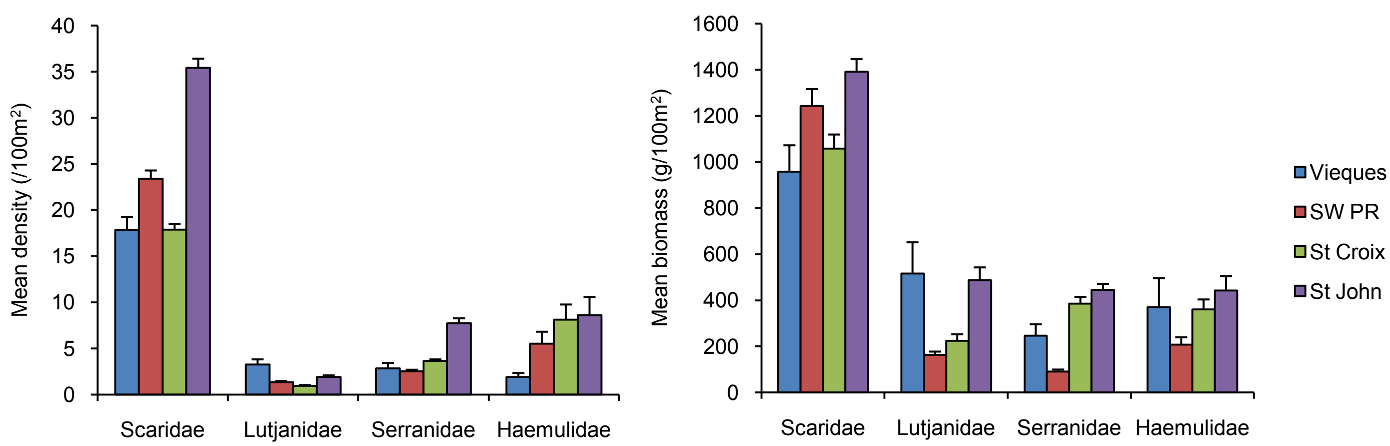


Figure 3.45. Estimated mean (±SE) density and biomass of key fish families in Vieques compared to other CCMA Biogeography Branch monitoring locations (2003-2007): La Parguera in SW Puerto Rico (n=450), St. Croix (n=714) and St. John (n=617).

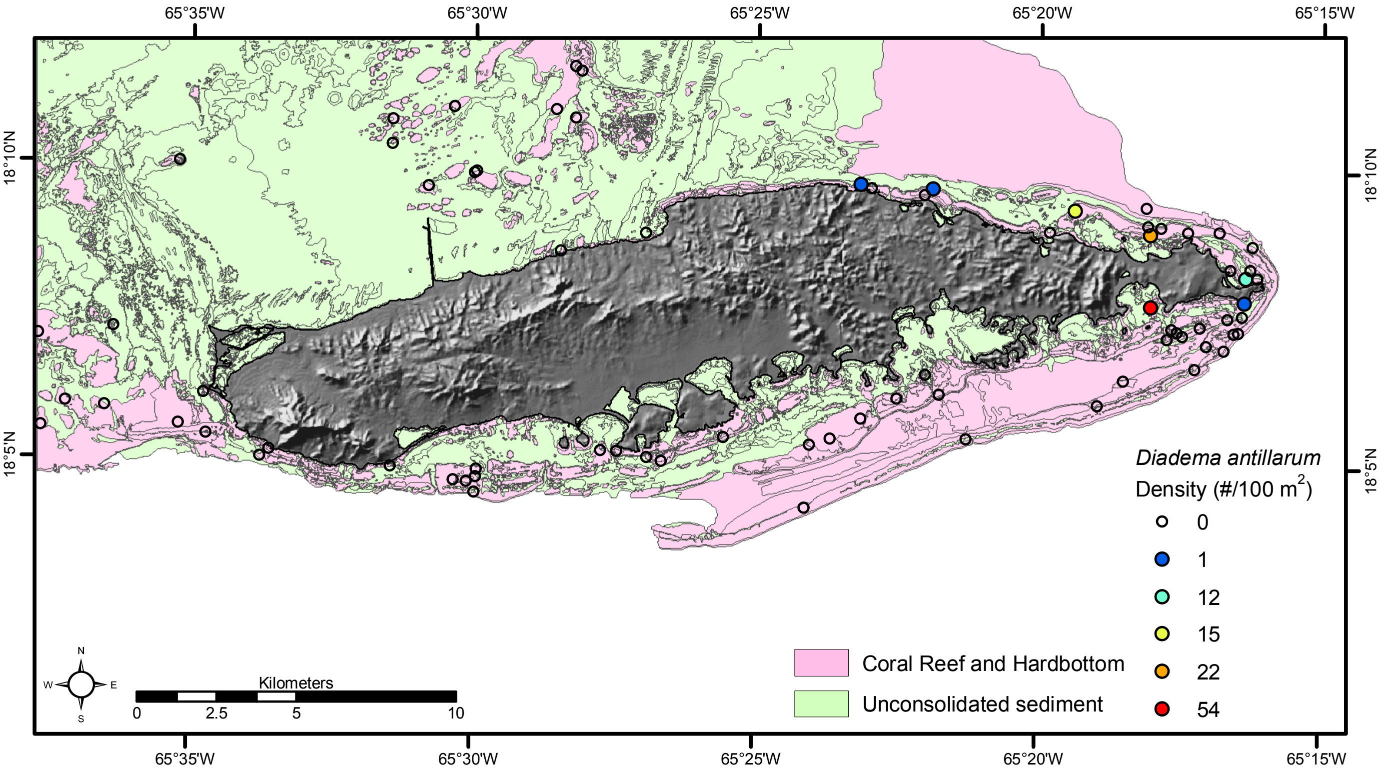


Figure 3.46. Spatial distribution of the long-spined urchin (*Diadema antillarum*).

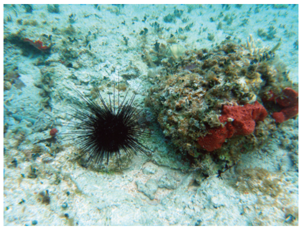
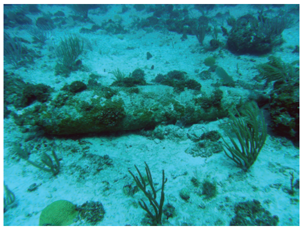


Image 3.12. *Diadema antillarum*. Photo: CCMA Biogeography Branch.

Image 3.13. Unexploded ordnance. Photo: CCMA Biogeography Branch.



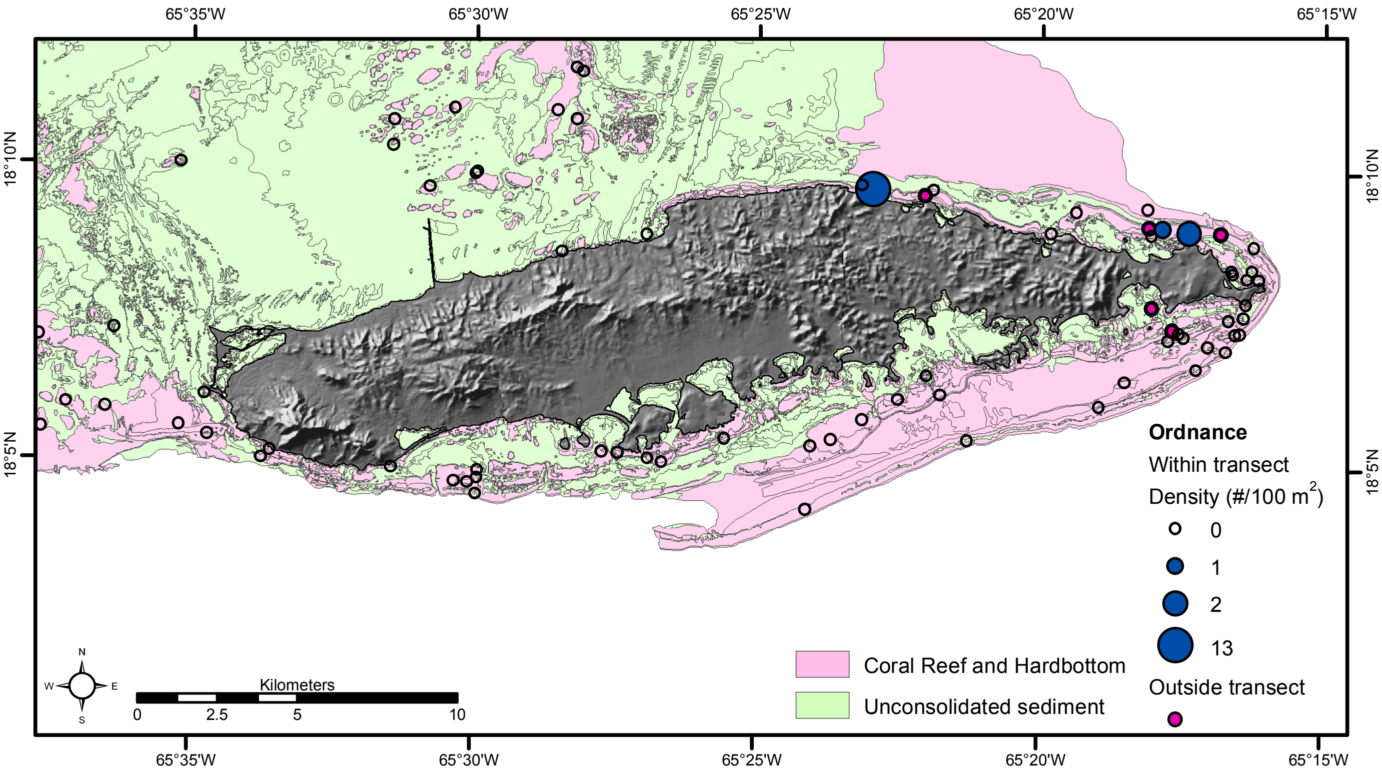


Figure 3.47. Spatial distribution of unexploded ordnance observed both within and outside survey transects.

3.4 SUMMARY AND CONCLUSIONS

Regular monitoring of the habitat and fish community in Vieques would allow potential changes to be followed over time, as well as to strengthen statistical comparisons between strata. In addition to local changes in land use and marine zoning, other regional factors are known to have affected benthic and fish communities in the greater Caribbean in recent decades. These include a widespread die-off of *D. antillarum* in the 1980s, mass mortality of Acroporids due to white-band disease, coral bleaching events, overfishing, and tropical cyclones. Due to the lack of consistent monitoring, there was a large gap in published reports quantifying fish abundance and benthic cover from the late 1980s-early 2000s. As such, the likely succession in Vieques reefs must be inferred from nearby regions, although a recent mapping analysis illustrated the progressive decline in *Acropora* in Bahia Salina del Sur from 1975-1985 (Hernandez-Cruz et al. 2006). Riegl et al. (2008) suggested that the primary cause of death of *Acropora* in Vieques was likely disease, while subsequent hurricanes aided in breaking up the dead stands into reef rubble. Benthic habitat composition on reef/hardbottom habitats in Vieques appears to be similar to other monitoring locations in the U.S. Caribbean, despite differences in management, land use and marine zoning between the various study areas. This supports the idea that present conditions on Vieques have been primarily shaped by regional-scale factors.

As this characterization was limited to one sampling period and a relatively small number of survey sites, it is difficult to make conclusive statements about fish and benthic cover metrics in relation to habitat and geographic location. For many habitat and fish metrics, there was often a large degree of variation within strata, resulting in a relatively large coefficient of variation (CV) of estimates of the mean (e.g., >20%). Despite the limitations, several interesting patterns emerged along the north vs. south shore of Vieques and also adjacent to the various land use strata from east to west. Many of the benthic and fish variables showed a gradual shift in abundance along one or both of these axes. These patterns are likely influenced by differences in reef morphology, habitat composition, bathymetry, hydrodynamics, and sedimentation. As demonstrated in Chapter 2, the composition and extent of benthic habitat structure around Vieques varies over space. For example, there is a higher amount of aggregated reef and pavement on the south shore of Vieques compared to the north side of the island. The southern coast is also marked by the presence of numerous bays and lagoons, many of which are lined by mangroves, which likely serve as nursery habitat and recruitment sources for many species (see Chapter 4). In contrast to the generally more topographically complex south shore, where the location of the shelf edge ranges approximately 1-4 km from shore, the area north of Vieques extending up towards Culebra is relatively uniform and shallow (<30 m) (Bauer et al. 2008).

Twentieth-century land use in Vieques is unique compared to other neighboring Caribbean islands due to the presence of the U.S. Navy from the 1940s-2003. There has been speculation that Naval activities, particularly firing exercises, have had a negative impact on marine biota. Conversely, one might expect that the lack of residential and commercial development on two-thirds of the island offered a degree of protection from anthropogenic activities (i.e., a de-facto marine protected area). Although there were some differences in fish and benthic communities across survey strata, our results do not support either of these hypotheses. Although coral cover was lowest in the strata north of the LIA (4-North), cover was only significantly lower when compared with the strata with the highest amount of cover (1-South). For most fish metrics, there was a stronger north-south trend than east-west. Although fisheries data for Vieques is inconsistent across years (see Bauer et al. 2008), interviews with fishermen indicated that primary fishing areas include the northern, eastern, and southeastern coasts of Vieques (Shivlani 2007; DON 1986).

A recent report summarizing data from the first five years of data collection in St. Croix illustrates the utility of regular monitoring in detecting changes over time and for informing marine spatial planning (Pittman et al. 2008). The transfer of lands from the U.S. Navy to the municipality and US. Fish and Wildlife are likely to result in a potential shift in development, runoff patterns, population demographics, and maritime activities such as fishing/diving. The results presented here are intended both to inform the current management decision-making process, as well as serve as a baseline for regular monitoring efforts. A spatially comprehensive assessment of softbottom habitat types (e.g., seagrass, mangrove) is also needed to fully characterize benthic and fish communities around Vieques. Regular monitoring of all habitats and associated communities are essential for conservation and management of Vieques' marine resources.

ACKNOWLEDGEMENTS

Randy Clark, Kimberly Edwards, Charles Menza, and Kimberly Foley assisted in the collection of field data in Vieques. Many thanks to Captain Angel Nazario (*Aquanauta*) and his assistant Joel (Joiito) Rivera for getting

us safely to/from our sites. Oscar Diaz (USFWS), Mark Martin (Vieques Conservation and Historical Trust), Carlos Bermudez (Vieques Divers), Carlton Finley, John Noles and Christopher Penny (NAVFAC Atlantic) provided invaluable logistical support before and/or during the field survey. Special thanks to Dave Green (PIKA) for accompanying the dive teams in potentially hazardous areas. Thanks to Charles Menza and Simon Pittman for providing helpful comments and editorial assistance. Many thanks to Jason Rolfe and Diane Wehner for their assistance and valuable discussions throughout this project. Funding for this work was provided by NOAA's Office of Response and Restoration and NOAA's Coral Reef Conservation Program.

LITERATURE CITED

Ault, J.S., S.G. Smith, J. Luo, M.E. Monaco, and R.S. Appeldoorn. 2008. Length-based assessment of sustainability benchmarks for several coral reef fishes in Puerto Rico. Environmental Conservation 35(3): 221-231.

Bauer, L.J., C. Menza, K.A. Foley, and M.S. Kendall. 2008. An ecological characterization of the marine resources of Vieques, Puerto Rico. Part I: Historical data synthesis. Prepared by National Centers for Coastal Ocean Science (NCCOS) Biogeography Branch in cooperation with the Office of Response and Restoration. Silver, Spring, MD. NOAA Technical Memorandum NOS NCCOS 86. 121 pp.

Beyer, H.L. 2004. Hawth's Analysis Tools for ArcGIS. Available at http://www.spatialecology.com/htools.

Caldow, C., R.Clark, K. Edwards, S.D. Hile, C. Menza, E. Hickerson and G.P. Schmahl. 2009. Biogeographic characterization of fish communities and associated benthic habitats within the Flower Garden Banks National Marine Sanctuary: Sampling design and implementation of SCUBA surveys on the coral caps. NOAA Technical Memorandum NOS NCCOS 81. Silver Spring, MD. 134 pp.

Clark, R., C. Jeffrey, K. Woody, Z. Hillis-Starr, and M. Monaco. 2009. Spatial and temporal patterns of coral bleaching around Buck Island Reef National Monument, St. Croix, US Virgin Islands. Bulletin of Marine Science 84(2): 167-182.

Clarke, K.R. and R.M. Warwick. 2001. Change in marine communities: an approach to statistical analysis and interpretation. 2nd Edition. PRIMER-E, Plymouth.

Cochran, W.G. 1977. Sampling Techniques. John Wiley and Sons, Inc., New York. 413 pp.

DON (Department of the Navy). 1979. Draft environmental impact statement for the continued use of the Atlantic Fleet Weapons Training Facility Inner Range (Vieques). Prepared by TAMS (Tippetts, Abbett, McCarthy, Stratton) and Ecology and Environment, Inc.

DON (Department of the Navy). 1986. Environmental assessment of continued use of the Atlantic Fleet Weapons Training Facility Inner Range, Vieques, Puerto Rico. Prepared by Ecology and Environment, Inc.

Froese, R. and D. Pauly (eds.). 2008. FishBase. World Wide Web electronic publication. www.fishbase.org, version (06/2008).

García-Cagide, A., R. Claro, and B.V. Koshelev. 1994. Reproducción. pp. 187-262. In: R. Claro (ed.) Ecología de los peces marinos de Cuba. Inst. Oceanol. Acad. Cienc. Cuba. and Cen. Invest. Quintana Roo (CIQRO) México.

Garcia-Sais, J.R., R.L. Castro, J.S. Clavell and M. Carlo. 2001. Baseline characterization of coral reef and seagrass communities from Isla de Vieques, Puerto Rico. Department of Marine Sciences, University of Puerto Rico, Mayaguez. 108 pp.

Garcia-Sais, J.R., R.L. Castro, J.S. Clavell and M. Carlo. 2004. Monitoring of coral reef communities from Isla de Vieques, Puerto Rico, 2004. Department of Marine Sciences, University of Puerto Rico, Mayaguez. 122 pp.

GMI (Geo-Marine, Inc.). 2003. Reef ecosystem baseline assessment survey and monitoring, Vieques Island, Naval Station Roosevelt Roads, Puerto Rico. Prepared for Atlantic Division, Naval Facilities Engineering Command, Norfolk, Virginia.

GMI (Geo-Marine Inc.). 2005. An assessment of the condition of coral reefs off the former Navy bombing ranges at Isla de Culebra and Isla de Vieques, Puerto Rico. Prepared for the Department of Defense, Legacy Resource Management Program, Arlington, Virginia, and US Army Corps of Engineers, Huntsville, Alabama.

Hernandez-Cruz, L.R., S.J. Purkis, and B.M. Riegl. 2006. Documenting decadal spatial changes in seagrass and *Acropora palmata* cover by aerial photography analysis in Vieques, Puerto Rico: 1937-2000. Bulletin of Marine Science 79(2): 401-414.

Kendall, M.S., C.R. Kruer, K.R. Buja, J.D. Christensen, M. Finkbeiner, R.A. Warner and M.E. Monaco. 2001. Methods used to map the benthic habitats of Puerto Rico and the U.S. Virgin Islands. NOAA Technical Memorandum NOS NCCOS CCMA 152. Silver Spring, MD. 45 pp.

Lundgren, I. and Z. Hillis-Starr. 2008. Variation in *Acropora palmata* bleaching across benthic habitats at Buck Island National Reef Monument (St. Croix, USVI) during the 2005 bleaching event. Bulletin of Marine Science 83: 441-451.

Miller, J.R., R. Waara, E. Muller and C.S. Rogers. 2006. Coral bleaching and disease combine to cause extensive mortality on reefs in U.S. Virgin Islands. Coral Reefs 25:418.

Pittman, S.J., S.D. Hile, C.F.G. Jeffrey, C. Caldow, M.S. Kendall, M.E. Monaco, and Z. Hillis-Starr. 2008. Fish assemblages and benthic habitats of Buck Island Reef National Monument (St. Croix, U.S. Virgin Islands) and the surrounding seascape: A characterization of spatial and temporal patterns. NOAA Technical Memorandum NOS NCCOS 71. Silver Spring, MD. 96 pp.

Riegl, B.M., R.P. Moyer, B. Walker, K. Kohler, D. Gilliam and R.E. Dodge. 2008. A tale of germs, storms, and bombs: geomorphology and coral assemblage structure at Vieques (Puerto Rico) compared to St. Croix (US Virgin Islands). Journal of Coastal Research 24(4): 1008-1021.

Shivlani, M. 2007. Community studies to determine the feasibility and expectations of marine protected area (MPA) management in Vieques, Puerto Rico. Unpublished report. 38 pp.

Zar, J.H. 1999. Biostatistical Analysis. Prentice Hall, New Jersey. 663 pp.

CHAPTER 4: COMPARATIVE SURVEYS OF BENTHIC SOFTBOTTOM HABITATS AND FAUNAL COMMUNITIES OF LAGOONS AND SHALLOW SHELVES OF THE ISLAND OF VIEQUES

John Selden Burke, W. Judson Kenworthy, Brian Degan, Jenny Vander Pluym, and Brooke Landry*

Center for Coastal Fisheries and Habitat Research, National Centers for Coastal Ocean Science, National Ocean Service, NOAA, 101 Pivers Island Road, Beaufort, NC 28516

**Corresponding author: john.burke@noaa.gov*

4.1 INTRODUCTION

In collaboration with NOAA's Office of Response and Restoration, the Center for Coastal Fisheries and Habitat Research (CCFHR) conducted surveys designed to assist in prioritizing conservation efforts of coastal waters around the Island of Vieques, Puerto Rico. Our focus was to identify and characterize areas of high ecological value by quantitatively sampling benthic habitats and their faunal communities. Annual surveys were conducted from 2005-2008 and were increasingly focused on the south coast of the island. This shift in focus was based on results that supported the hypothesis that the southern shelf represented a more complex ecological system. Evidence of this geographic difference is apparent in the species richness, diversity, abundance and the trophic structure of the fish communities and is detailed in Chapter 3 of this volume (Figures 3.17, 3.26). Such a difference might be expected based on the greater topographical complexity of the southern shelf (Chapter 2), including the presence of numerous bays and lagoons. This chapter focuses on the sampling conducted in four lagoon systems and two shallow shelf regions around the island.

A lagoon can be defined as a comparatively shallow, semi-protected salt or brackish water body separated from the deeper water by shallow or exposed features. Tropical lagoon systems range from brackish inland bodies of water receiving only intermittent exchange with the coastal ocean, to coastal bays whose seaward margins are bounded by a submerged barrier, either sand or reef. These protective features buffer the physical impact of the coastal ocean, providing an environment that differs from more exposed coastal areas and fostering the development of unique and complex habitats. The margins of lagoons often represent ecotones where trapped terrestrial sediment and the development of mangroves stands support diverse faunal and floral communities which serve as nurseries for many marine species. Lagoons are especially important to fisheries and wildlife providing food and shelter for a variety of ecologically and commercially important species. Four lagoons, Puerto Mosquito, Puerto Ferro, Ensenada Honda, Puerto Negro and two areas on the insular shelf of Vieques (Figure 4.1) were surveyed to provide data on the flora of benthic habitats and the composition and density of their faunal community. By comparing the physical and biological characteristics of these lagoons to similar communities of the open shelf, inference on the role of lagoons in Vieques' marine ecosystem is provided.

4.2 METHODS

Research cruises

Four research cruises were conducted aboard NOAA's RV Nancy Foster in the vicinity of southeastern Puerto Rico and Vieques (Table 4.1) between 2005 and 2008. The cruises were part of a large multi-disciplinary study of southeastern Puerto Rico designed to characterize benthic habitats, examine disturbance and recovery dynamics of seagrasses, and assess the use of benthic habitats by fish and wildlife resources (e.g., Manatees).

Table 4.1. Summary of the number of sites sampled to characterize the benthic habitat and associated faunal communities in lagoons (Ensenada Honda, Puerto Ferro, Puerto Mosquito and Puerto Negro) and the Northwest and Southern Shelf softbottom habitats during annual research cruises off the coast of Vieques, 2005 to 2008.

Cruise	Dates	Benthic Habitat				Epibenthic and Fish Community		
		Visual Surveys		Seagrass Biomass		SCUBA pushnet		Visual Surveys
		Lagoon	Shelf	Lagoon	Shelf	Lagoon	Shelf	Ensenada Honda
2005	Feb 18 - Feb 26	6	28	0	0	0	0	6
2006	Apr 05 - Apr 14	100	20	100	20	0	0	10
2007	Apr 28 - May 05	29	43	0	0	29	0	13
2008	Mar 27 - Apr 04	0	41	0	0	0	41	0

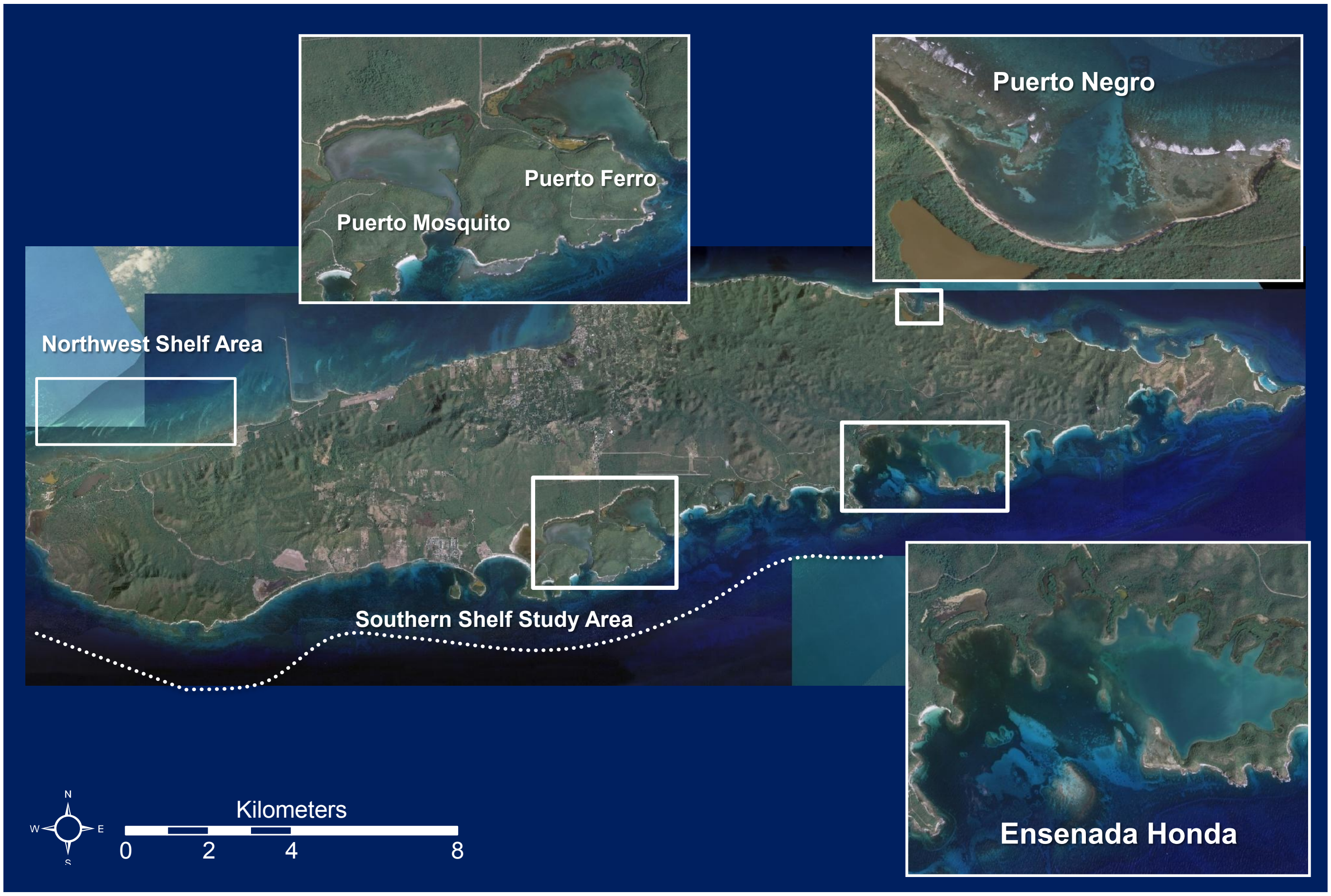


Figure 4.1. Aerial imagery showing study sites around the Island of Vieques. White rectangles indicate the four lagoons sampled to characterize benthic habitats and estimate fish density. Also indicated are the northwest and southern shelf study area.

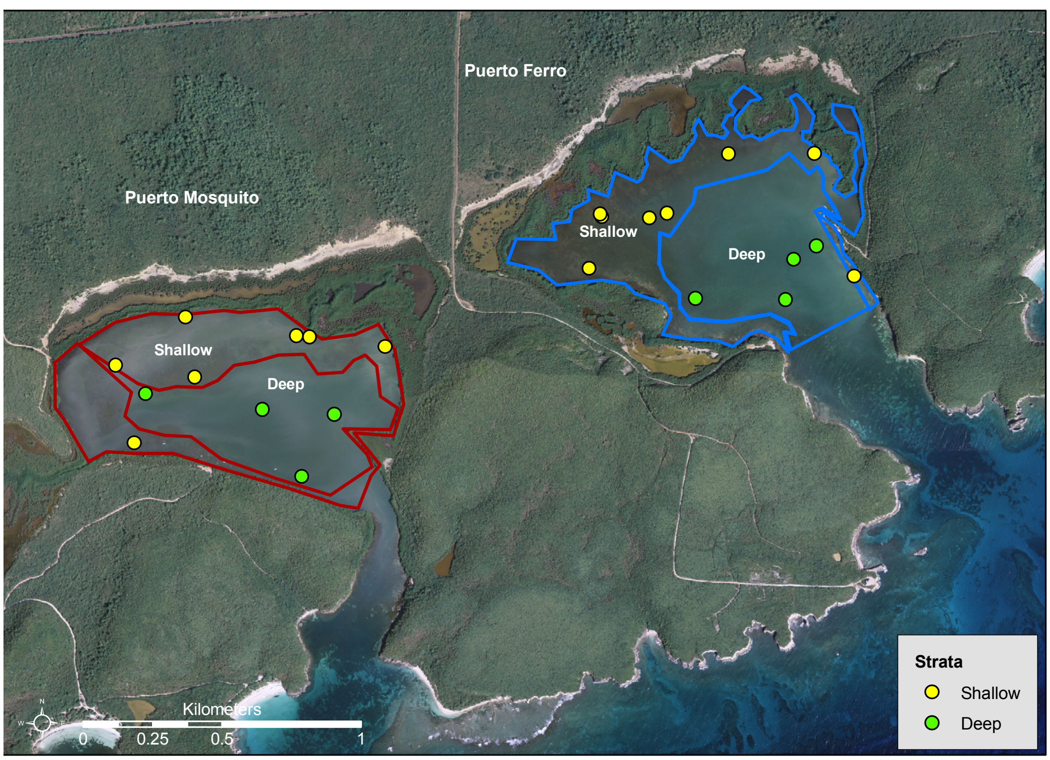


Figure 4.2. Aerial photograph of Puerto Ferro (0.656 km^2) and Puerto Mosquito (0.655 km^2) showing deep and shallow sampling strata and location of randomly selected stations.

Study Areas

Lagoon sites

Puerto Mosquito and Puerto Ferro, adjacent lagoons on the south coast of Vieques (Figure 4.1), are managed by the Puerto Rico Department of Natural Resources (PRDNR) and the US Fish & Wildlife Service (USFWS) as part of one of the largest wildlife reserves in the Caribbean (http://www.fws.gov/caribbean/Refuges/PDF/vieques_factsheet.pdf). Differences in water clarity and benthic habitats are apparent between these lagoons. Puerto Mosquito is a relatively shallow lagoon (< 4 m) surrounded almost entirely by mangroves (Figure 4.2). It has a narrow mouth that restricts exchange with coastal waters and provides a unique

physical environment for the bioluminescent dinoflagellate, *Pyrodinium bahamense*. High densities of this dinoflagellate make Puerto Mosquito one of the brightest bioluminescent bays (biobays) in the world (Mitchell 2005). Puerto Ferro, located just east of Puerto Mosquito, is slightly deeper (4-5 m) with a wider mouth and channel that provides greater water exchange with the Caribbean Sea. Consequently, waters within Puerto Ferro are less turbid than Puerto Mosquito.

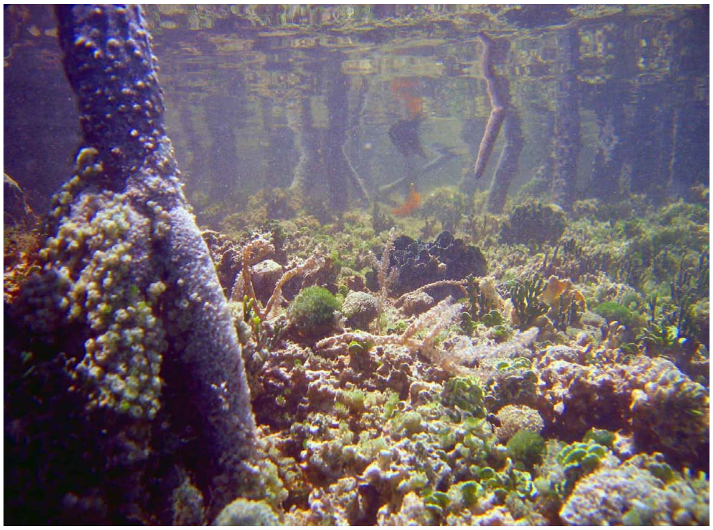


Figure 4.3. Underwater photograph of macroalgae growing among red mangrove prop roots along the lagoon margin.

Benthic habitats are inherently altered by variations in light penetration to the bottom due to variation in depth, shading and water clarity. Difference in water clarity is likely responsible for differences in the benthic habitats of the two lagoons. Much of the deeper basin of Puerto Mosquito is un-vegetated whereas Puerto Ferro supports a more diverse benthic flora that changes with depth. Shading from the mangrove canopy plays an important role in habitat structure at the margins of these two lagoons. Where the mangrove stands have extended into relatively deep water (>1 m) and the canopy is thick, the substrate largely lacks vegetation. In contrast, where the mangrove margin is shallow and sufficient light penetrates the canopy, macro-algal beds develop among the prop roots (Figure 4.3). As the lagoon margins extend out into shallow flats they are carpeted with seagrasses. Both lagoons support mixed species communities dominated by *Thalassia testudinum* (turtle grass), but the turbid water of Puerto Mosquito support more *Halodule wrightii* (shoal grass) and *Ruppia maritima* (widgeon grass). The latter two species are more tolerant to lower light conditions and fluctuating environments than *T. testudinum.* In deeper zones of Puerto Mosquito, light levels diminish and a shift from seagrass to bare bottom occurs. In contrast, in the relatively clear waters of Puerto Ferro where seagrass beds extend into deeper water, macroalgae replaces seagrass beds as dense stands of calcareous species *Udotea*, *Penicillus* and *Halimeda sp.* (Figure 4.4). In still deeper waters, where the bottom is subjected to intense bioturbation and light is limiting, dense meadows of the small, opportunistic sea grass *Halophila decipiens* (paddle grass) develop on the sediment mounds and pits resulting from burrowing shrimp (*Callianassa sp*., Figure 4.5).

Figure 4.4. Underwater photograph of the mid–depth zone of Puerto Ferro where the benthic habitat transitions from seagrass into a lush bed of macroalgae visited by a school of spotfin moharra.

The third lagoon studied, Ensenada Honda, is a large and complex system located to the east of Puerto Ferro and protected from the open sea by promontories, islands and a shallow barrier of reefs. The degree of protection varies spatially resulting in a range of environmental conditions (Figure 4.6). The system has two rather distinct zones. The eastern zone is largely isolated from the sea by a promontory of land and from the western zone by a shallow sill. Water in the eastern zone is relatively turbid reducing light penetration so that the mud bottom of the deep central basin lacks vegetation. The western zone receives

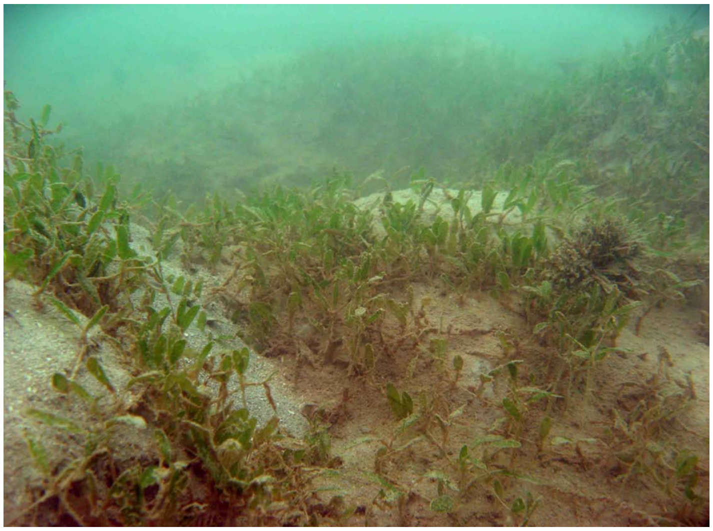


Figure 4.5. Underwater photograph of the deepest regions of Puerto Ferro where *Halophila decipiens* grows on mounds of sediment excavated from shrimp burrows.

protection from the sea by a shallow reef and islands; however, several deep channels ensure water exchange. Waters of the western zone are clear and the bottom supports dense seagrass beds and scattered patch reefs. The landward margin of the lagoon of both zones supports a mangrove fringe.

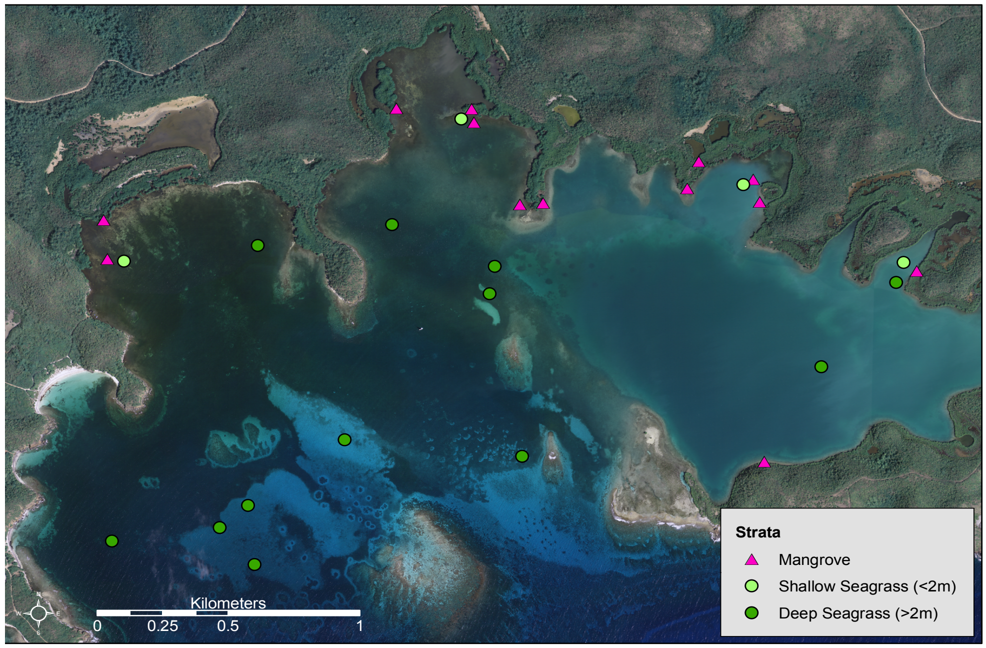


Figure 4.6. Aerial photograph of Ensenada Honda (4.9 km^2) showing sampling stations in three different habitat strata: 1) mangrove fringe, 2) shallow seagrass (<2m), and 3) deep seagrass (>2m).

The fourth lagoon site, Puerto Negro, is on the north coast of Vieques and provides a contrast to those on the south coast. Puerto Negro is an open coastal lagoon protected by a fringing reef divided by a deep central channel (Figure 4.7). The landward margin of the lagoon is a beach feature which separates the inner portion of the lagoon from a mangrove wetland. Waters of the lagoon are very clear and much of the bottom is covered with dense seagrass beds that consist primarily of *T. testudinum* with lesser amounts of *Syringodium filiforme* (manatee grass). This lagoon appears to provide ideal habitat for manatees, which were observed on all visits to the site.

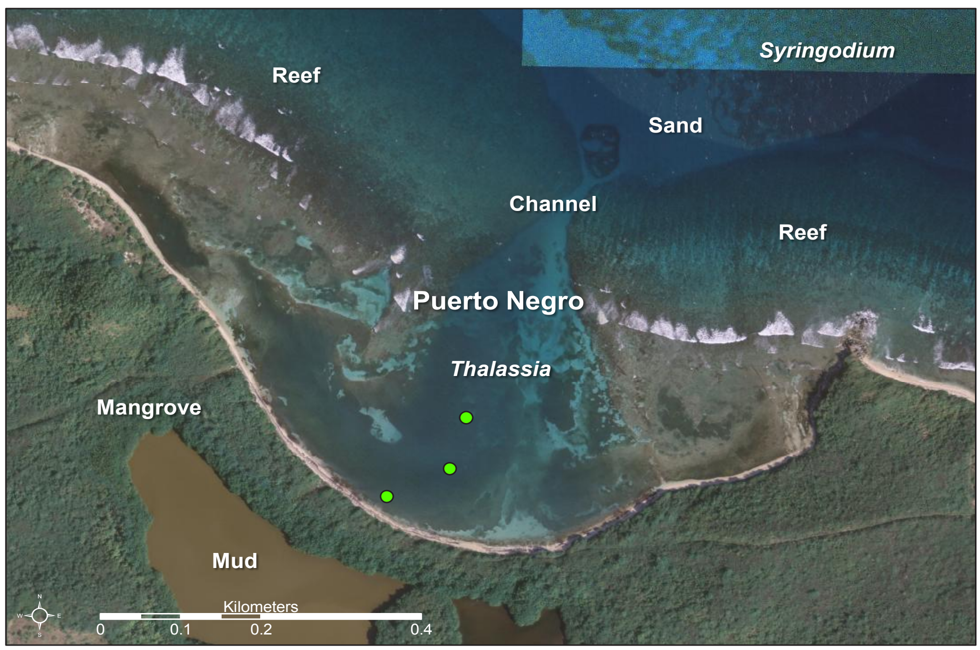


Figure 4.7. Aerial photograph of Puerto Negro (0.22 km^2) showing study locations and the general distribution of habitat types including reef, sand, *Thalassia*, *Syringodium*, mangrove and mud.

Shelf Sites

Investigations of two shallow shelf areas (Figure 4.1) are presented: 1) an extensive seagrass bed on the northwest coast, and 2) the shallow shelf extending from just offshore of Ensenada Honda to the western end of the island of Vieques (Figure 4.8). On the northwest shelf our objective was to characterize the benthic vegetation (species composition, density and biomass of seagrass and density of macroalgae). On the south coast we provide a more general characterization of benthic vegetation on the shallow softbottom (density estimates of seagrasses and macroalgae) and estimates of the epibenthic fauna that utilize this habitat. In both shelf areas, sites were randomly selected from depth strata of 0 to 10 m. For benthic habitat characterization, twenty sites were chosen from the 12.8 km^2 area of the northwest shelf and 43 sites from the 22.4 km^2 area on the southern shelf.

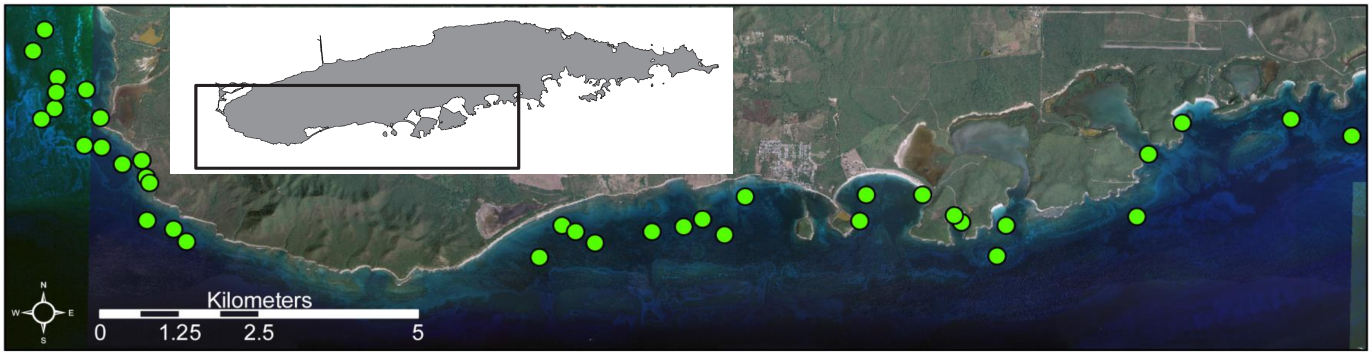


Figure 4.8. Aerial photograph showing location of study sites sampled visually for habitat characteristics and with the SCUBA pushnet to characterize the benthic fauna of seagrass beds on the Southern Shelf of Vieques.

Epibenthic Community Sampling

Benthic plant communities

During the 2006 cruise benthic plant communities were characterized in Puerto Ferro, Puerto Mosquito and the northwest coast by: 1) visually assessing the plant cover and density in 0.25 m^2 quadrats at pre-selected random points using a modified Braun-Blanquet method (Mueller-Dombois and Ellenberg 1974; Fourqurean et al. 2001), and 2) measuring shoot density and biomass in 15 cm diameter sediment cores at pre-selected random points (n = 50 for Puerto Mosquito and Puerto Ferro and n = 20 for the northwest coast).

On the southern shelf (n=43), in Ensenada Honda (n=13) and Puerto Negro (n=16) we visually characterized the benthic plant communities by the Braun-Blanquet method at randomly selected locations in the same manner as for Puerto Ferro, Puerto Mosquito, and the northwest Vieques coast. No biomass or shoot density samples were collected at Puerto Negro, Ensenada Honda or the southern shelf study area.

Figure 4.9.Two divers conducting SCUBA pushnet sampling in a mixed seagrass/macroalgae bed on the southern shelf of Vieques.

Benthic fauna SCUBA pushnet survey

During the 2007 and 2008 cruises epibenthic faunal communities were sampled with a 2 m wide, fine mesh (3 mm) SCUBA pushnet (Table 4.1). The SCUBA pushnet (Figure 4.9) was used to sample epibenthic fauna from seagrass beds of lagoons in 2007 (Figures 4.2, 4.7) and the southern coast shelf (Figure 4.8) during our 2008 cruise. The SCUBA pushnet effectively samples cryptic species that shelter in the macrophytes and are therefore under-sampled by visual techniques. During a standard sample, a pair of divers pushed the net over the substrate for a distance of 30 m, thus sampling an area of 60 m^2. To account for depth-related habitat differences, Puerto Mosquito and Puerto Ferro were both stratified with respect to depth and sampling locations were randomly selected from deep (>2 m) and shallow (<2 m) strata (Figure 4.2). On the southern shelf of Vieques sampling locations were randomly selected from the shelf area less than 10 m in depth. SCUBA pushnet collections were sorted in the field and fishes that could be identified to species were measured for total length and released. Animals whose identification could not be determined in the field were preserved in 70% alcohol and returned to the laboratory for positive identification.

Fish community visual survey

During the 2005, 2006 and 2007 cruises, visual survey samples of fish communities were collected from Ensenada Honda. The lagoon was stratified by habitat type and depth. Three softbottom strata including mangrove margins, shallow (<2 m) and deep (2-10 m) softbottom vegetated substrate were sampled using a band transect visual survey method. Divers counted and estimated lengths of fishes along a 30 m x 2 m band

transect following the temporal stratification transect method outlined by Samoilys and Carlos (2000). Counting was temporally stratified to capture those fish most likely to flee at the approach of a diver. Looking ahead over a section of the band transect, divers first counted large fishes and then counted the cryptic and small sedentary fishes while slowly swimming that section. This methodology provided estimates of both sedentary fishes, which ignore a diver's presence and can only be accurately counted from a small area, and large fishes, that often distance themselves from an approaching diver and will be missed in counts when area is strictly limited. Visual identification of fishes was made to species or the lowest taxonomic group possible based on criteria provided by Humann and Deloach (2002). Lengths of all fishes counted were estimated by tallying fish to length intervals; 1-2 cm, 2-3, 3-5, 5-10, 10-15, 15-20, 20-30, 30-35 cm. Lengths of fishes greater than 35 cm were visually estimated to the nearest decimeter.

Data Analysis

Where appropriate, statistics for macrophyte and faunal abundance are presented graphically as means ± their standard errors. For SCUBA pushnet samples family diversity was calculated using the Shannon index (Pielou 1977).

4.3 RESULTS AND DISCUSSION

Benthic Plant Communities

Overall, the highest relative abundance of total seagrass cover was recorded in Puerto Negro, followed closely by the northwest Vieques and southern Vieques shelves, Ensenada Honda, Puerto Ferro and finally, Puerto Mosquito (Figure 4.10).

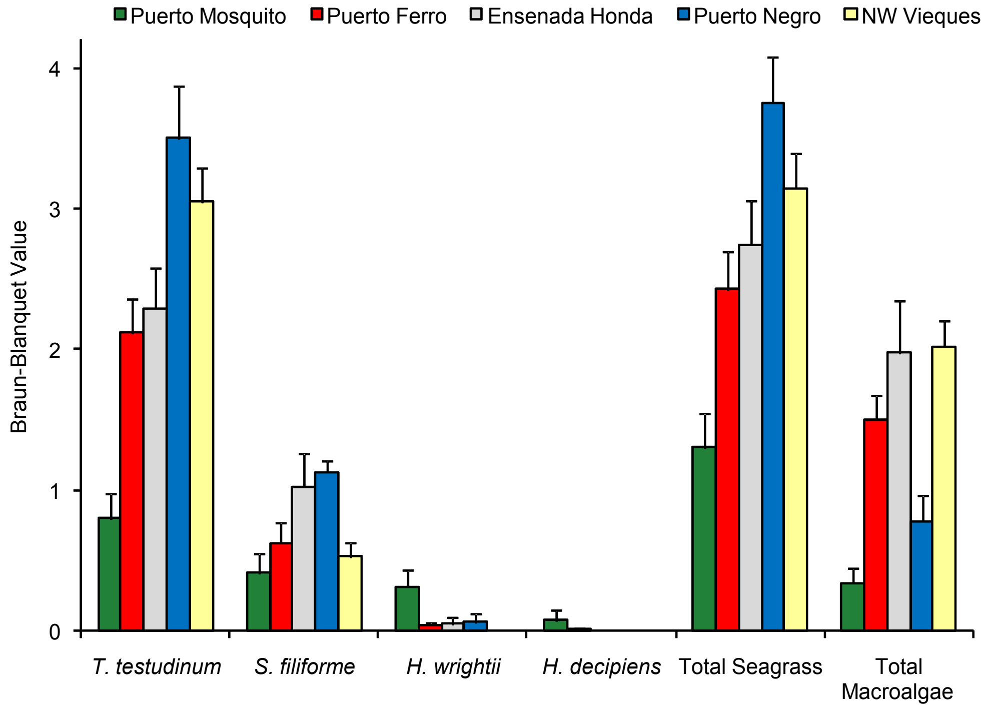


Figure 4.10. Mean (± SE) Braun-Blanquet cover scores for seagrasses and total macroalgae from the northwest shelf study areas and four lagoon systems ordered by increasing turbidity: Puerto Negro, Ensenada Honda, Puerto Ferro and Puerto Mosquito.

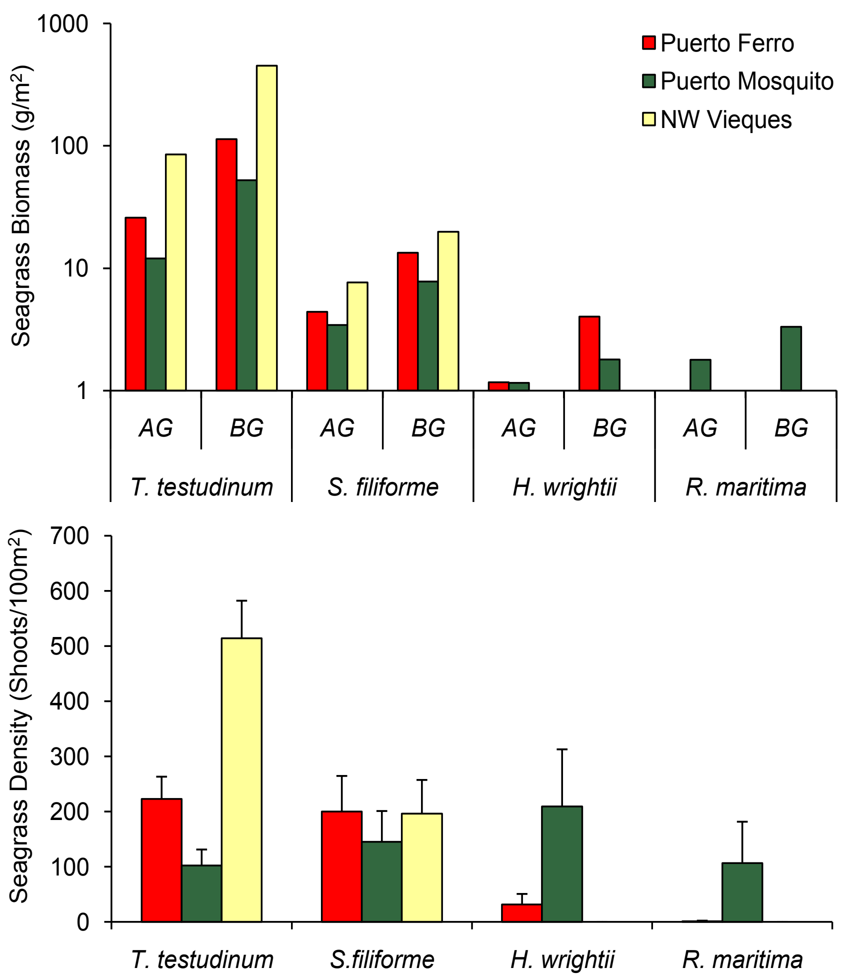


Figure 4.11. Seagrass biomass (gdw/m^2) and density (shoots/m^2) (±SE) from Puerto Ferro, Puerto Mosquito, and the northwest Vieques coast. The top graph shows seagrass biomass on a log scale and therefore does not include standard error values. AG and BG refer to above and below ground biomass.

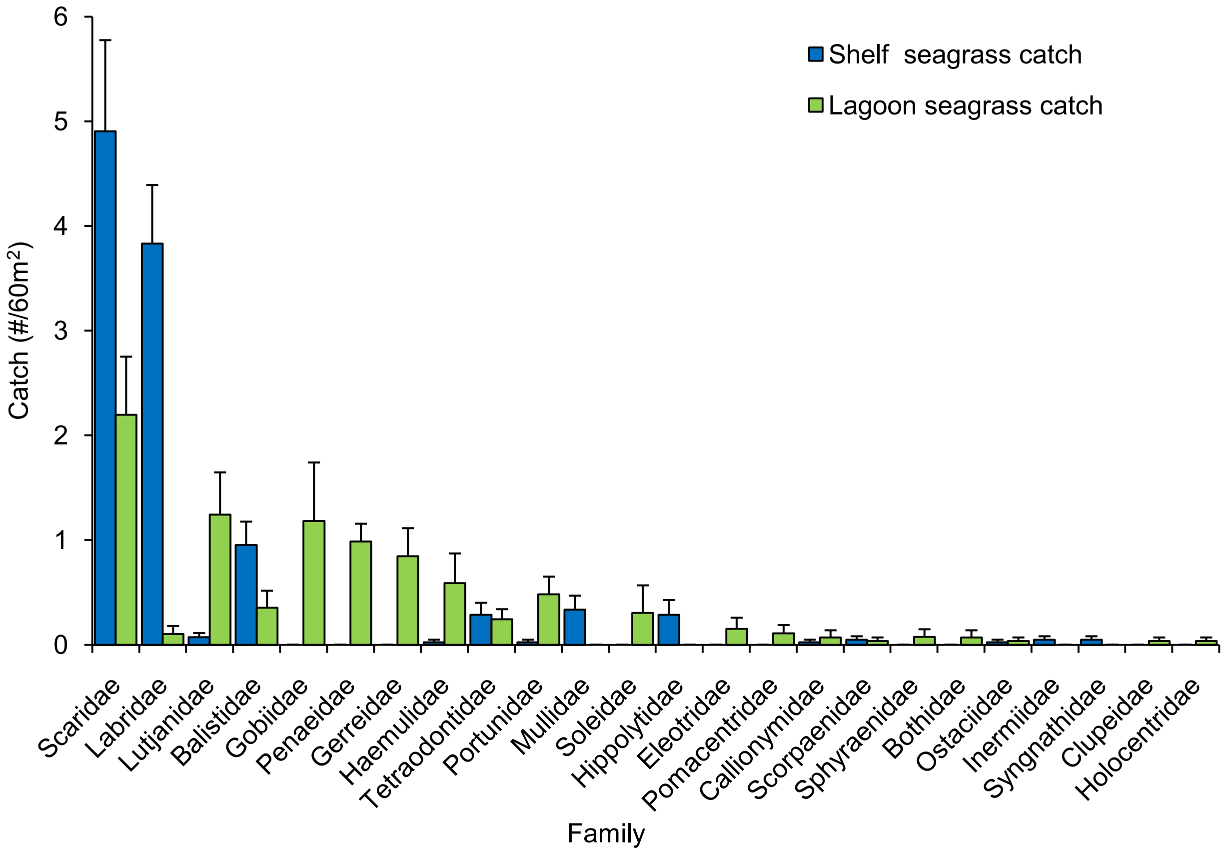


Figure 4.12. Comparison of SCUBA pushnet catch from southern shelf seagrass beds and lagoon seagrass beds. Mean (±SE) catches are presented for all families sampled in the surveys.

Ensenada Honda and the northwest Vieques coast study area had similar and relatively high cover of macroalgae followed by Puerto Ferro, the southern coast, Puerto Negro and then Puerto Mosquito. *Thalassia testudinum* dominated the seagrass cover at most of the sites, as is typical of tropical oligotrophic seagrass ecosystems found throughout the Caribbean. The one exception was the southern shelf where *S. filiforme* densities were slightly higher. Comparison of seagrass biomass between the enclosed lagoons of Puerto Ferro and Puerto Mosquito and the northwest Vieques coast study area shows biomass was also dominated by *T. testudinum* at all three areas and *T. testudinum* biomass was highest in the northwest Vieques coast study area (Figure 4.11). The largest difference between the sites was seen in *H. wrightii* biomass; it was relatively more abundant in Puerto Mosquito than Puerto Ferro and completely absent from the northwest Vieques shelf. Another important difference between these lagoons is the presence of *R. maritima* in Puerto Mosquito but nowhere else. *Halophila decipiens* was observed in the seagrass cover in the enclosed lagoons of Puerto Ferro and Puerto Mosquito (Figure 4.10), but not in the northwest Vieques coast, Puerto Negro or Ensenada Honda.

Figure 4.13. SCUBA pushnet sample of juvenile fishes from Puerto Mosquito. Numbered fishes include: 1) *Ocyurus chrysurus*, 2) *Monacanthus sp.*, 3) *Lutjanus apodus*, 4) *Haemulon plumeri*, 5) *Lutjanus synagris*, 6) *Lutjanus griseus*, 7) *Haemulon scirius*, 8) *Sparisoma radians*, 9) *Scarus iseri*, 10) *Eucinostomus melanopterus*.

Lagoon and Shelf Fauna

SCUBA pushnet surveys

Comparison of SCUBA pushnet samples from lagoon seagrass beds and those of the open southern shelf of Vieques indicate a striking difference in the composition of their faunal assemblages (Figure 4.12). Although both

assemblages were similar in density (lagoon: 9.2±1.1/60m^2, shelf: 10.9±1.4/60m^2) and consisted almost entirely of juveniles, the Shannon diversity index indicated that the lagoon assemblage was more diverse at the family level (1.2±0.1 vs 0.8±0.1). The shelf seagrass bed assemblage was dominated by two reef fish families, Scaridae and Labridae, whose densities appear to be higher on the shelf than in lagoons. Though Scaridae were also abundant in lagoons, a wide variety of other families were also common. Common species included both softbottom and reef associated animals that were either absent or rare in shelf samples. Compared to the shelf, lagoons had a high proportion of juveniles representing commercially important fish and crustacean families including four snapper species, three grunts, great barracuda, a Penaid shrimp and a Portunid crab species.

Differences among faunal communities were also evident in the three lagoons sampled with the SCUBA pushnet. Catches in all three lagoons were dominated by juveniles fishes (Figure 4.13). Fish communities, similar in Puerto Mosquito and Puerto Ferro, differed markedly from Puerto Negro (Figure 4.14). Only four families, all representing reef fish, were caught in Puerto Negro and the catch was dominated by yellowtail snapper (*Ocyurus chrysurus*), a commercially important member of the family Lutjanidae. The higher richness at the family level of Puerto Mosquito and Puerto Ferro was also evident at the species level. The snapper family represented by a single species in Puerto Negro was represented by four species in Puerto Mosquito and three in Puerto Ferro (Figure 4.14). In addition to these commercially important species that are associated with coral reef as adults, the rich faunas of Puerto Mosquito (14 families) and Puerto Ferro (15 families) also included relatively high densities of juvenile crustaceans such as the commercially important southern brown shrimp that as an adult associates with softbottom habitats (Grady 1971). Similar scuba net surveys of a range of lagoon and shelf habitats in the Bay of La Parguera in South Western PR yielded similar results. While the juvenile fish community observed in lagoons varied relative to specific habitat characteristics, fish diversity and the number and density of commercially important species was higher in lagoon than shelf habitats.

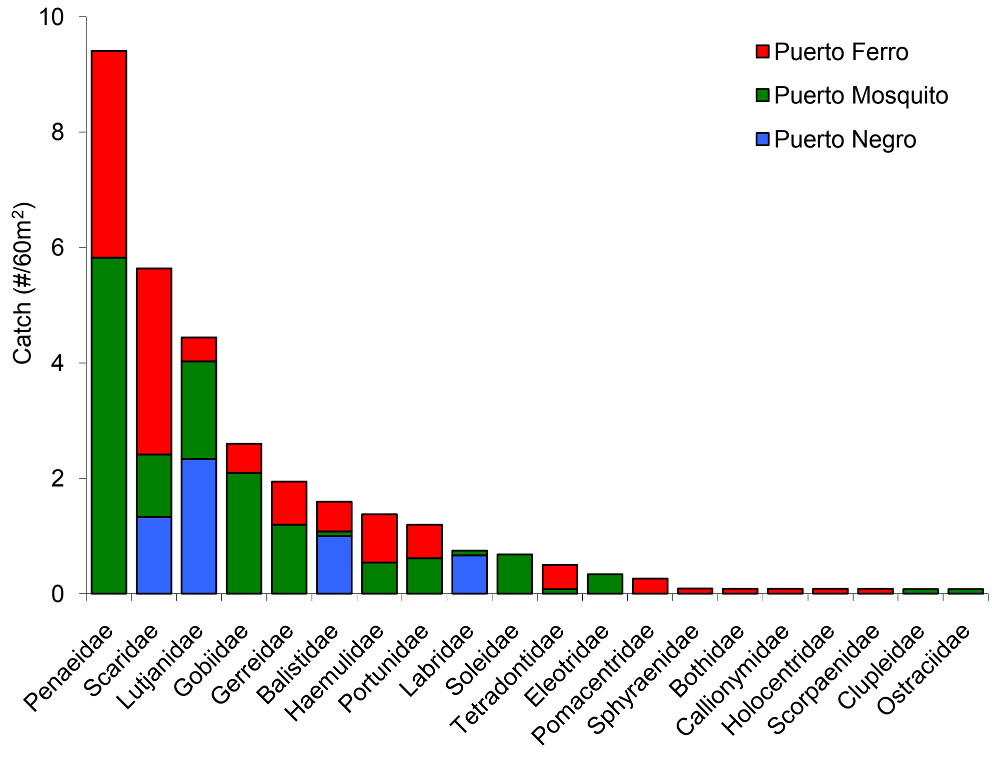


Figure 4.14. Comparison of animal densities (catch/60 m^2) in SCUBA pushnet samples by family for three lagoons (Puerto Ferro, Puerto Mosquito, Puerto Negro).

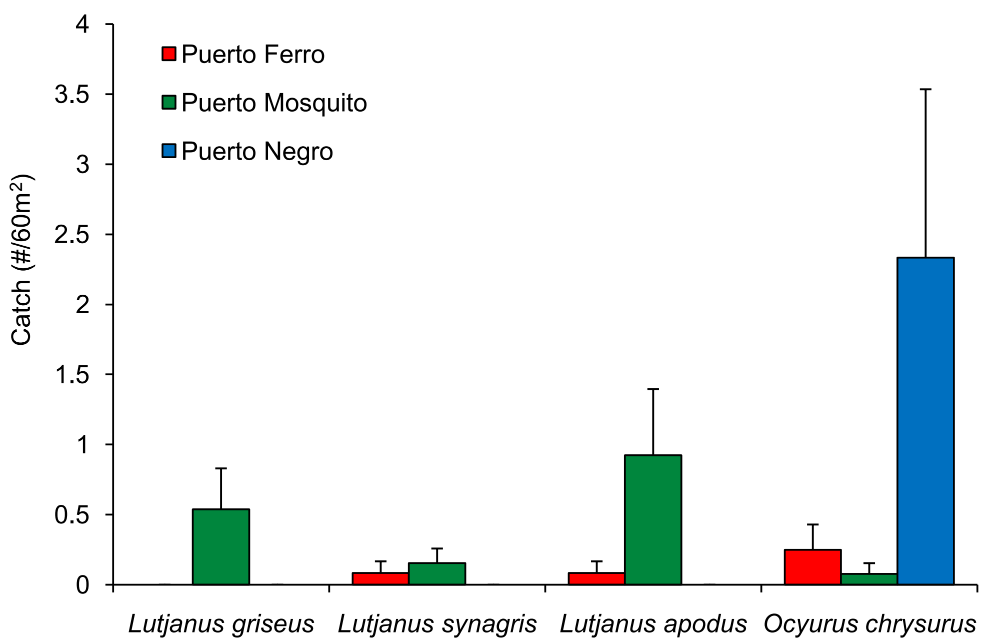


Figure 4.15. Comparison of mean density (±SE) of four Lutjanid species between three lagoons (Puerto Ferro, Puerto Mosquito, Puerto Negro).

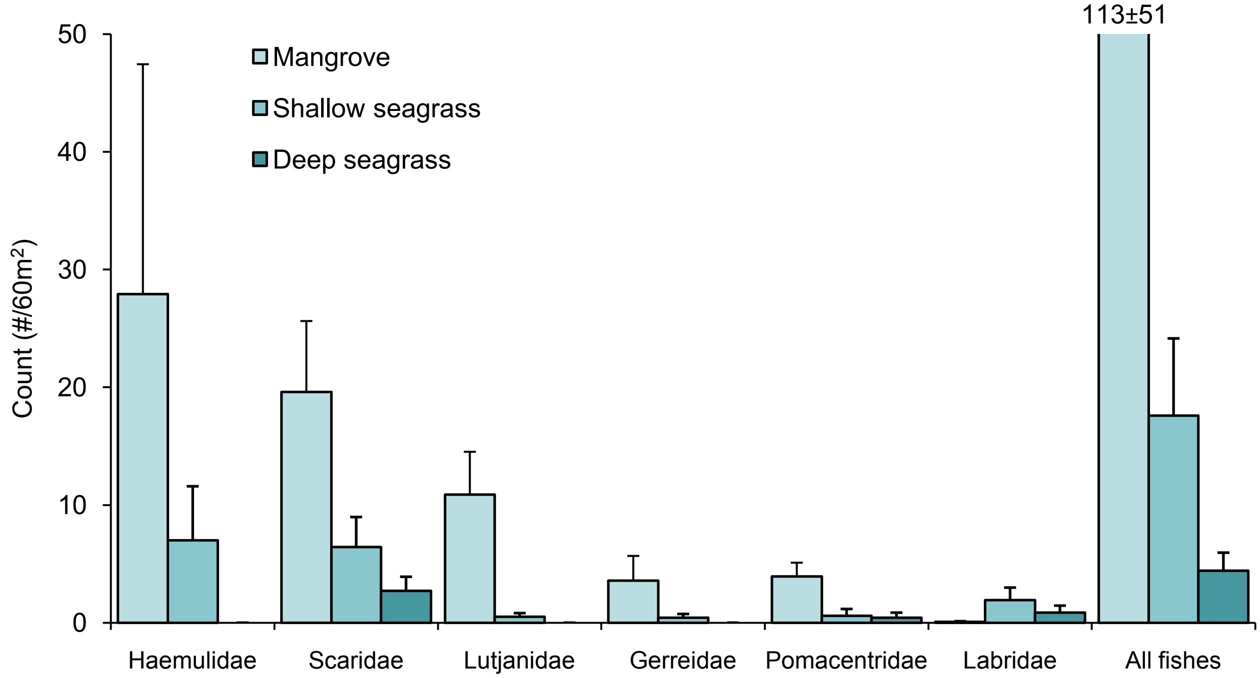


Figure 4.16. Comparison of counts in visual surveys of important reef fish families and total fish counts from three habitat strata (mangrove fringe, shallow seagrass, deep seagrass) sampled in the Ensenada Honda lagoon system.

Visual surveys

Visual survey data from Ensenada Honda showed that densities of fishes differed among the softbottom habitats of the lagoon (Figure 4.16). For major reef fish families present in the lagoon, highest densities were observed at the mangrove fringe among and adjacent to the mangrove prop roots, intermediate densities in shallow seagrass beds and lowest densities in deep seagrass beds. The sole exception to this generalization was for wrasses (Labridae), which appeared to avoid the mangrove fringe. On average, total fish counts were much higher from the mangrove habitat due to the contribution of forage fishes, including juveniles of the families Gerridae, Clupeidae (herrings) and Engraulidae (anchovies), which were seldom observed over open seagrass beds.

4.4 SUMMARY AND CONCLUSIONS

The seagrass habitats that characterize the softbottom communities of Vieques are of outstanding quality and appear to play a critical role in the ecology of the island's coastal system. The diversity and abundance of seagrass meadows in the lagoons and on the shelves of Vieques are comparable to seagrass ecosystem elsewhere in the Caribbean Sea (Green and Short 2003). While the broad extent of the northern shelf supports more extensive sea grass beds than the narrower southern shelf (Chapter 2), the presence of numerous lagoons along the southern shore fosters greater variation in softbottom environments and seagrass habitats. These lagoons and the adjacent shelf are linked by the abundant seagrass meadows that provide continuous corridors of benthic habitat connecting the two systems.

Seagrass habitat variation among the lagoons surveyed in Vieques is largely dependent on variation in their connection to the coastal ocean and the amount of water exchanged between the shelf and the lagoons. Highest seagrass species richness was observed in Puerto Mosquito and Puerto Ferro whose exchange with the shelf was constrained relative to other lagoons surveyed. In the tropical seagrass ecosystem, these less oligotrophic conditions allow for the development of opportunistic species such as *H. wrightii* and ruderal species such as *H. decipiens*. In the most extreme case, Puerto Mosquito, we observed *Ruppia maritima* which is a ruderal species capable of growing in a wide range of salinities from nearly fresh water to 60 ppt. Ensenada Honda and Puerto Negro represent relatively open lagoon systems and their softbottom flora was similar to that of the shelf, more typical of the shallow water oligotrophic climax seagrass communities dominated by *T. testudinum* (Williams 1990) (Figures 4.10, 4.11).

The diversity of the epibenthic fauna of softbottom communities of Vieques corresponds with the richness of their flora. SCUBA pushnet samples from the shelf and lagoons suggest that the more diverse vegetated

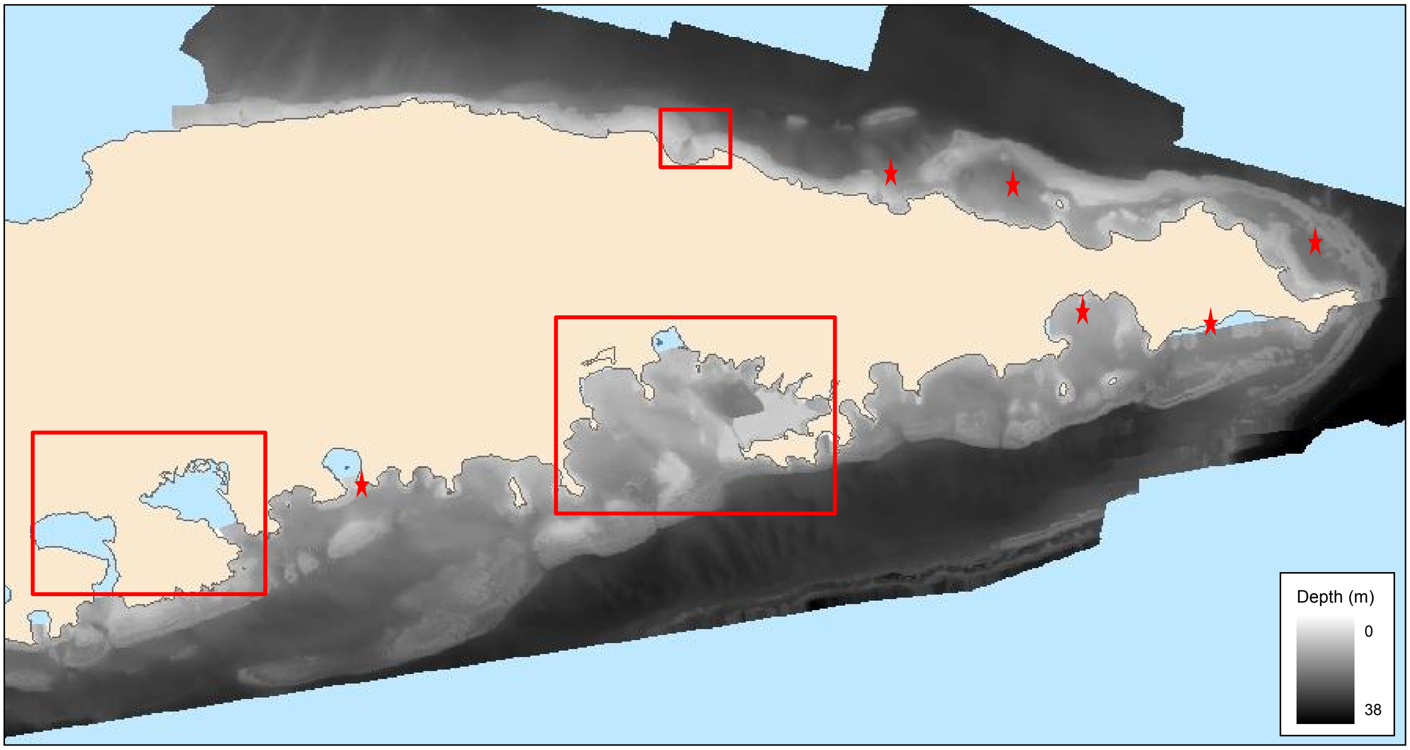


Figure 4.17. Coastal bathymetry from Scanning Hydrographic Operational Airborne Lidar Survey (SHOALS) data for eastern Vieques, collected at 400 soundings per second. The data shown were resampled to a 5 x 5 m pixel size. Lagoons sampled during our surveys are enclosed by boxes. Relative depths are represented by shading; light gray indicates shallower water, dark gray, deeper. Stars indicate additional lagoon systems that are relatively unknown.

habitats of the lagoons (Figures 4.3, 4.4, 4.5) shelter a more diverse faunal community (Figure 4.12). A similar relationship is evident within the lagoons themselves. The more diverse floral habitats of Puerto Mosquito and Puerto Ferro supported richer softbottom fauna than Puerto Negro (Figures 4.13, 4.14). Differences in the faunal communities among the three lagoons may relate in part to differences in turbidity levels, apparent in the aerial photography (Figures 4.2, 4.6, 4.7). Much of this variation in turbidity among lagoons results from differences in exchange with the shelf and subsequent effects on plankton densities and suspended materials; for example, dinoflagellate densities can be two orders of magnitude higher in Puerto Mosquito than Puerto Ferro and three orders greater compared to a well flushed lagoon (Gasparich 2007). The relatively dense plankton community of lagoons can be expected to enhance food availability and affect the foraging efficiency of both juvenile fishes and their predators. Turbidity levels appear to influence faunal composition of the lagoons at the family level. Although flatfish were sampled in both Puerto Mosquito and Puerto Ferro, members of the family Soleidae, which sense prey by taste and touch, were sampled in Puerto Mosquito while Bothid flounders, which are visual feeders, were collected in Puerto Ferro. Turbidity levels may also have influenced abundance and diversity within the family Lutjanidae. Grey, lane, and schoolmaster snappers had highest densities in Puerto Mosquito while yellowtail snapper were most abundant in Puerto Negro (Figure 4.14). This may relate to differences in feeding habits between these fishes as the yellowtail snapper feeds diurnally while the other three species are primarily benthic nocturnal feeders.

The concentrations of juveniles within lagoons of a variety of species whose adults occupy the shelves indicate that lagoons serve as nursery areas (Adams and Ebersole 2002; Nagelkerken 2007; Burke et al. 2009). Within Ensenada Honda a gradient in density of fishes relative to depth was apparent suggesting that the shallow vegetated habitats of this lagoon are of particular importance as nurseries (Figure 4.16). The shallow regions of the lagoons may be selected by juvenile fishes due to its quality in terms of providing shelter from predators as well as the availability of food resources. The presence of submerged mangrove root habitat at the margins of lagoons bordering the southern shelf appeared to attract juvenile fishes as seen in other locations throughout the Caribbean (Rooker and Dennis 1991; Nagelkerken 2007). The presence within lagoons of high concentrations of early juvenile stages of ecologically and commercially important species rare or absent from reef and hardbottom habitats (Chapter 3) and from shelf seagrass beds (Figure 4.12) indicates that the lagoons of Vieques are an integral part of the life history of these species and critical to their recruitment as advanced juveniles and adults to shelf habitats. Similar results, showing the importance of shallow lagoon systems as critical nursery areas, have been provided from mainland Puerto Rico (Burke et al. 2009) and elsewhere in the Caribbean (Adams and Ebersole 2002).

Although much remains to be learned about the lagoons of Vieques, we believe there is strong evidence that they play a vital role in the ecology of the coastal ecosystem. All lagoons share the characteristic of a connection to the adjacent shelf. Variation in this connectivity fosters variation in physical conditions that allow development within lagoon systems of a particularly broad range of tropical marine habitats. Another common attribute of the majority of lagoon habitats is the presence of seagrasses. This common structural component dominates the benthic landscape, providing important ecological services to and linkage between softbottom habitats that extends from the mangrove communities of the lagoons across the adjacent shelf to depths of >20m.

The high floral and faunal diversity of lagoons and evidence of their role as nursery areas for commercially and ecologically important species suggest these systems should receive protection from activities that would threaten their physical structure and environmental quality. From the perspective of conserving marine biodiversity and fostering sustainable fisheries, the distribution of lagoons and near-shore habitat generally has led us to conclude that the southern shelf and eastern end of the island appear particularly valuable. The bathymetry of this region is complex and possesses a wide variety of lagoon like systems in addition to those described in this study (Figure 4.17). Further studies are needed to more completely characterize the lagoons of Vieques, their linkage to the insular shelf and their role in sustaining the resources of the island's marine ecosystem.

ACKNOWLEDGEMENTS

We would like to thank the many individuals who made this work possible through planning, logistical support, field assistance, and diving. The Captain and crew of the NOAA Ship RV Nancy Foster provided the platform and logistical assistance on three research cruises to southeastern Puerto Rico. Staff and financial support from NOAA's Office of Response and Restoration was invaluable. Special thanks go to Kevin Kirsch and Sean Meehan for logistical and field support. Staff from the Center for Coastal Fisheries and Habitat Research (CCFHR) assisted in planning and implementing the cruises, sample processing and data analysis. CCFHR staff included Mark Fonseca, Amy Uhrin, Christine Addison, Paula Whitfield, Jenny Vander Pluym, Don Field, Lisa Wood, Shay Viehman, Mike Lacroix, Brad Teer, John Hackney, and Erika Hansen. Assistance was also provided through collaboration with the Florida Fish and Wildlife Conservation Commission including Manuel Merello, Penny Hall, Jennifer Kunzelman, Donna Berns, Kevin Madley, and Mark Julian. Todd Kellison and Mike Judge from the Miami Laboratory, NMFS provided diving and fish identification support. Warren Mitchell, North Carolina State University, assisted with the Hydro-acoustical study. Collaboration with Jim Reid, Sirenia Project, USGS, was instrumental in all phases of the benthic habitat work. Many thanks go to Jose Montalvo and support staff from the former Naval Facility at Naval Station Roosevelt Roads. Funding was provided by the Center for Coastal Fisheries and Habitat Research, the National Centers for Coastal Ocean Science, NOAA's Office of Response and Restoration, and NOAA's Office of Marine and Aviation Operations.

LITERATURE CITED

Adams A.J. and J.P. Ebersole. 2002. Use of back-reef and lagoon habitats by coral reef fishes. Marine Ecology Progress Series 228: 213-226.

Burke, J.S., W.J. Kenworthy and L. Wood. 2009. Ontogenetic patterns of concentration indicate lagoon nurseries are essential to common grunts stocks in a Puerto Rican bay. Estuarine, Coastal and Shelf Science 81: 533-543.

Fourqurean, J.W., A. Willsie, C.D. Rose, and L.M. Rutten. 2001. Spatial and temporal pattern in seagrass community composition and productivity in south Florida. Marine Biology 138: 341-354.

Gasparich, S. 2007. The concentration and distribution of bioluminescent dionflagellates in Vieques, Puerto Rico. 20th Annual Keck Symposium. Retrieved February 27 2009 from http://keck.wooster.edu/publications. 149-154.

Grady, J.R. 1971. The distribution of sediment properties and shrimp catch on two shrimping grounds on the Continental shelf of the Gulf of Mexico. Proceedings of the Gulf and Caribbean Fisheries Institute 23:139-148.

Green, E.P. and F.T. Short. 2003. World Atlas of Seagrasses. Prepared by the UNEP World Conservation Monitoring Centre. University of California Press, Berkeley, USA.

Humann, P. and N. Deloach. 2002. Reef Fish Identification. New World Publications, Jacksonville, Florida. 481 pp.

Nagelkerken, I. 2007. Are non-estuarine mangroves connected to coral reefs through fish migration. Bulletin of Marine Science 80: 595-607.

Mitchell, L E. 2005. Developing a GIS of the bioluminescent bays on Vieques, Puerto Rico. Retrieved March 18, 2007, from http://gis.esri.com/library/userconfproc04/docs/pap1018.pdf.

Mueller-Dombois, D. and H. Ellenberg. 1974. Aims and Methods of Vegetation Ecology. John Wiley & Sons, New York. 547 pp.

Pielou, E.C. 1977. Mathematical Ecology. John Wiley & Sons, New York. 385 pp.

Rooker, J.R. and G.D. Dennis. 1991. Diel, lunar and seasonal changes in a mangrove fish assemblage off southwestern Puerto Rico. Bulletin of Marine Science 49: 684-694.

Samoilys, M. A. and G. Carlos. 2000. Determining methods of underwater visual census for estimating the abundance of coral reef fishes. Environmental Biology of Fishes 57: 289-304.

Williams, S.L. 1990. Experimental studies of Caribbean seagrass bed development. Ecological Monographs 60: 449-469.

CHAPTER 5: ASSESSMENT OF CHEMICAL CONTAMINANTS IN SEDIMENTS AND CORALS IN VIEQUES

Anthony S. Pait, Andrew L. Mason, David R. Whitall, John D. Christensen, and S. Ian Hartwell*

Center for Coastal Monitoring and Assessment, National Centers for Coastal Ocean Science, National Ocean Service, NOAA, 1305 East-West Highway, Silver Spring, MD 20910

Corresponding author: tony.pait@noaa.gov

5.1 INTRODUCTION

The goal for this component of the ecosystem characterization in Vieques was to quantify the level of chemical contaminants in sediments and coral tissues from nearshore waters, and contaminants in sediments from a series of inland lagoons, in support of the environmental restoration efforts in Vieques. Objectives were to: 1) collect and analyze sediments from sites throughout the nearshore waters and inland lagoons for organic (e.g., hydrocarbons) and inorganic (e.g., trace elements, typically metals) contaminants; 2) collect and analyze samples of mustard hill coral (*Porites astreoides*) for residues of the same organic and inorganic contaminants; and 3) collect and analyze sediments for residues of energetics (i.e., explosives).

Image 5.1. Beach at Bahia Salina del Sur.

5.2 METHODS

Sampling Design

The sediment sample sites for the current study were selected using a stratified random sampling design. Similar to the fish/habitat characterization (Chapter 3), nearshore waters around Vieques were divided into five north and five south strata (Figure 3.1). NOAA's 2001 benthic habitat map (Kendall et al. 2001) was used to generate a data layer of sampleable soft bottom sediments. A spatially-articulated random-stratified technique was then used to optimize for statistical generalization over the sediments in the study area. The sediments were collected from both nearshore waters and from a number of inland lagoons in May 2007. The 55 sites where sediments were collected and analyzed are shown in Figure 5.1. Following these collections, a request was made by NOAA's Office of Response and Restoration for an additional sampling of sediments from inland lagoons in Vieques to further characterize these areas. Sample sites within the inland lagoons were selected using a random-stratified technique. Twenty-three sediment samples were collected in October 2007 (Figure 5.1, three character site designations). Because the sites sampled in October 2007 were also selected randomly within the lagoons, the data generated could be combined with the results from the May 2007 sampling. The results of this second collection also enabled comparisons between nine inland lagoons in Vieques. Sites where *P. astreoides* were collected are shown in Figure 5.2. Some of the coral sampling sites were co-located with the Biogeography Program dive sites. Coral tissues were collected under permit 06-IC-056 issued by the Puerto Rico Department of Natural and Environmental Resources (DNER). A total of 35 coral samples collected in May 2007 were analyzed for this project. Typically, coral and sediment sites were not collocated; there were two sites, however, where both *P. astreoides* and sediments were collected.

Sampling Protocols

Sediments sampled in the former U.S. Navy property and in the civilian areas were collected by hand. Samples were collected in this manner due to the possibility of subsurface unexploded ordnance located in the former Vieques Naval Training Range (VNTR) on the eastern half of the island, and the Naval Ammunition Support

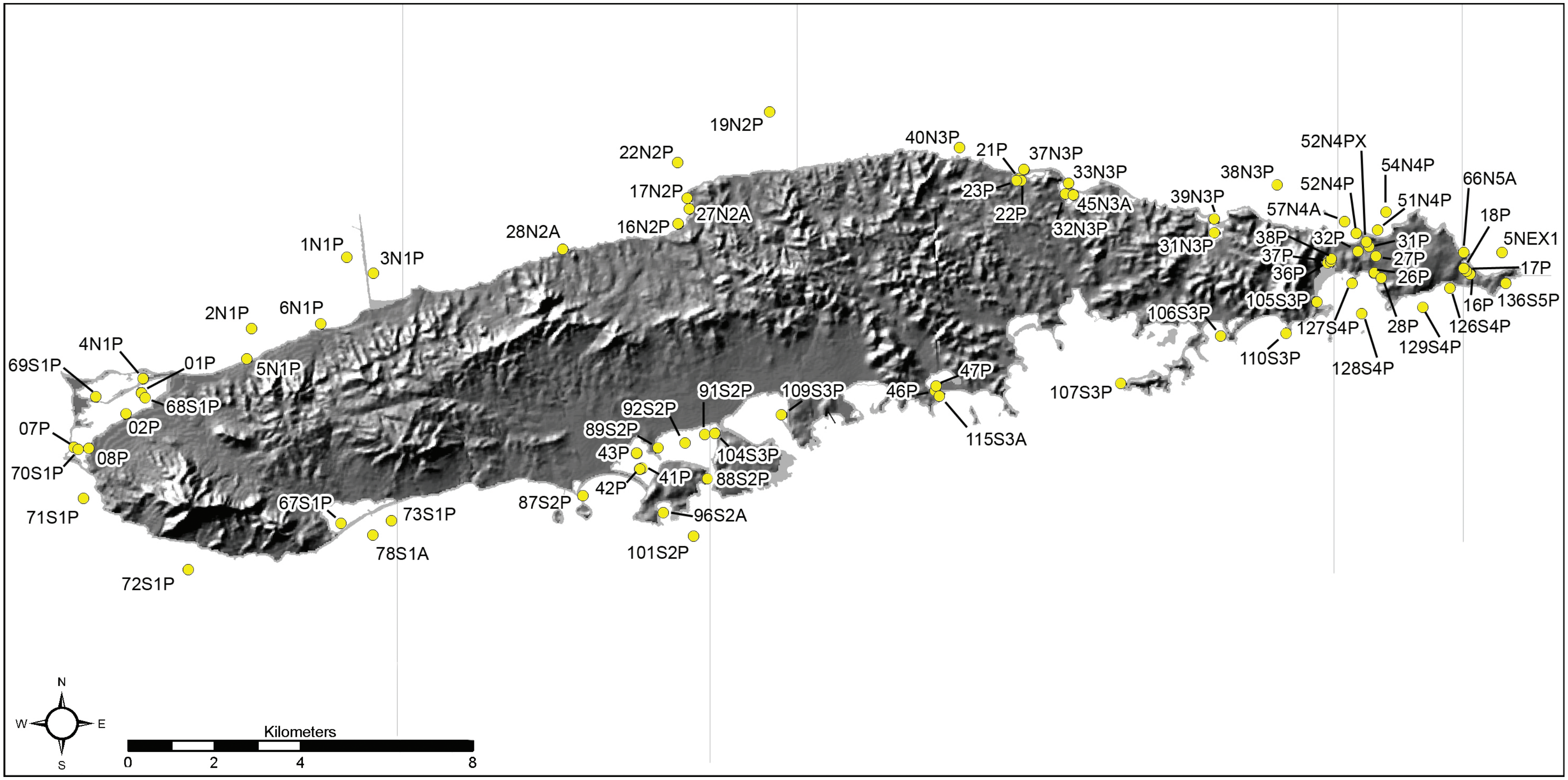


Figure 5.1. Sediment sites analyzed in Vieques (May and October 2007). Letters represent primary or alternate (P or A) sites or sites on the north or south (N or S) shore of Vieques. Three letter designations (e.g., 08P) represent October 2007 inland lagoon site designations.

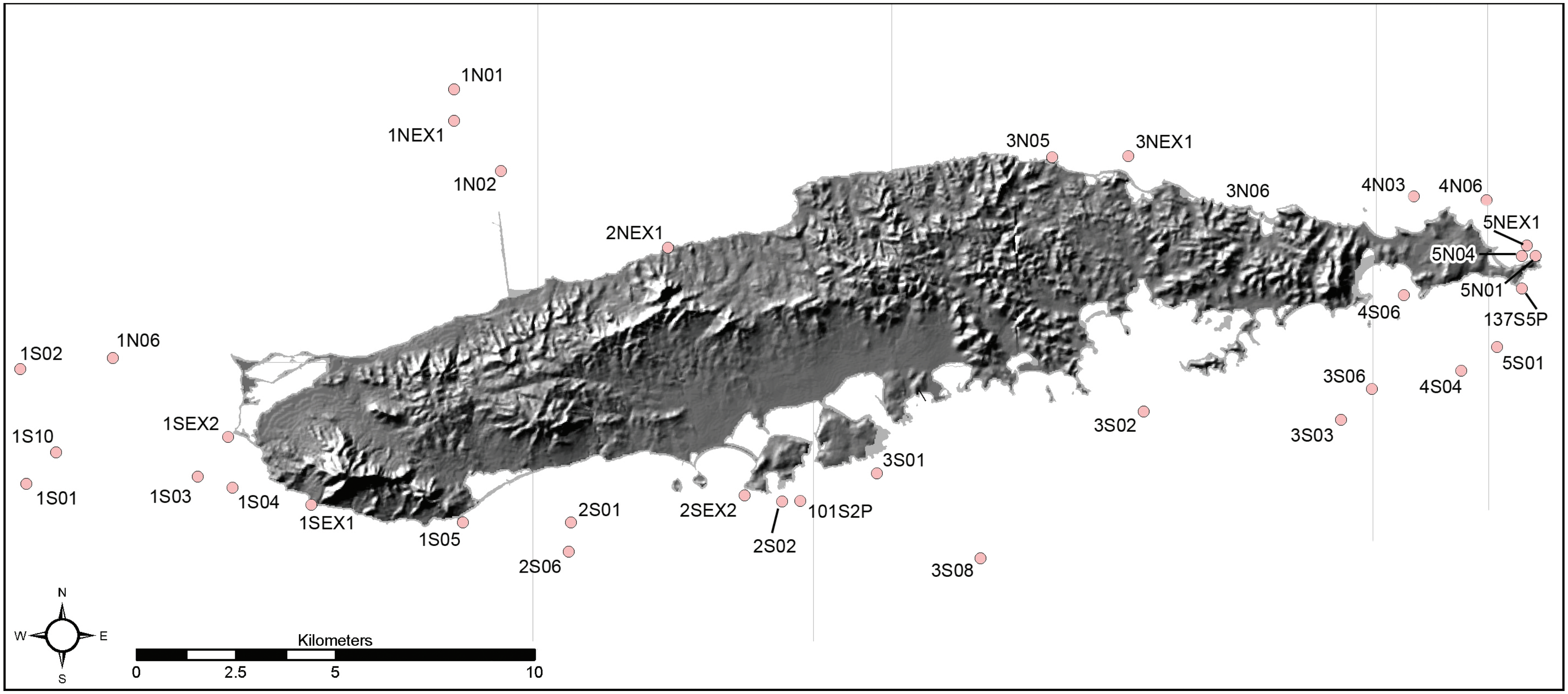


Figure 5.2. Coral sites analyzed. Letters (N or S) designate sites on the north or south shore of Vieques.

Detachment (NASD) in the western portion of Vieques. When sampling the VNTR or NASD areas, a U.S. Navy UXO (unexploded ordnance) safety contractor (e.g., PIKA International or CH2MHILL) accompanied NOAA's Center for Coastal Monitoring and Assessment (CCMA) personnel, and tested the area with a metal detector prior to sample collection, to ensure the safety of the operation. Samples were collected by scooping the top 3 cm of sediment into two certified clean IChem® 250 ml jars. CCMA personnel collecting the samples wore disposable nitrile gloves to avoid contaminating the sample. In deeper waters, sediment samples were collected by CCMA SCUBA divers from the vessel *Aquanauta*. A sediment sample was also collected for grain size. Once collected, the sediment samples were placed on ice in a cooler. At the end of each day, samples for contaminant analysis were frozen at -15°C in a freezer at the headquarters of the Vieques National Wildlife Refuge (VNWR), operated by the U.S. Fish and Wildlife Service (USFWS). The samples collected for grain size analysis were placed in a refrigerator rather than frozen, to avoid altering the grain size structure of the sediment. At the end of the mission, samples were shipped overnight to the laboratory (TDI-Brooks International in College Station, TX) for analysis. Prior to analysis, samples were stored at -20°C.

Image 5.2. CCMA diver sampling the coral *P. astreoides* in Vieques.

The coral samples were taken by NOAA SCUBA divers in May 2007 using a hammer and titanium punch (see inset). Titanium was used as it was not a target trace element for this project. As with sediment sampling, a U.S. Navy UXO safety contractor diver accompanied NOAA divers in the areas offshore of the former VNTR and NASD areas, first testing the site with a metal detector, to ensure the safety of the personnel, before the coral sample was collected. Prior to each use, the punch was rinsed with acetone to minimize cross-contamination. Divers collecting the coral samples also wore disposable nitrile gloves. The diver hammered the titanium punch into the coral head which produced a coral core with a diameter of approximately 1.5 cm and a similar core length. Approximately 20 cores were taken at each site and placed underwater in an IChem® certified clean 250 ml jar and then capped. The jar was brought to the surface, drained of water and placed on ice. At the end of each day, the samples were placed in a freezer (-15 ºC) at the VNWR. At the end of the mission, samples were shipped overnight to the laboratory for analysis. A series of water parameters (dissolved oxygen, temperature, salinity, and conductivity) were measured at each site using a YSI® salinity/conductivity/temperature meter. In nearshore waters, surface and bottom readings were taken. In the shallower inland lagoons, only surface readings were made.

Chemical Contaminants Analyzed

The list of chemical contaminants analyzed in the sediment and coral samples for this project is shown in Table 5.1. The samples were analyzed as part of NOAA's National Status and Trends (NS&T) Program within CCMA. For over 20 years, NS&T has monitored the Nation's estuarine and coastal waters for chemical contaminants in bivalve mollusk tissues and sediments. Work to characterize chemical contaminants as part of CCMA's ecological characterizations in tropical waters, represents a recent expansion of NS&T activities. NS&T regularly quantifies approximately 150 organic and inorganic contaminants. The compounds analyzed include 58 polycyclic aromatic hydrocarbons (PAHs), 31 organochlorine pesticides, 38 polychlorinated biphenyls (PCBs), four butyltins, and 16 trace and major elements. All samples were analyzed using NS&T analytical protocols. The analytical protocols for organics (Kimbrough et al. 2006) and trace and major elements (Kimbrough and Lauenstein 2006) have previously been published. Each of the contaminant classes analyzed for this project are discussed below. In addition, sediment samples were analyzed for 15 energetics (explosives) or related compounds.

PAHs

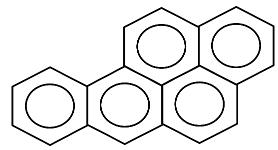
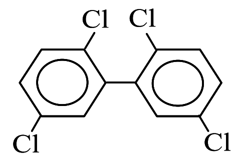
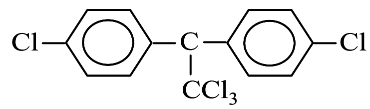
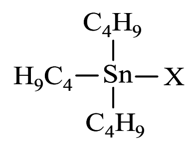
Polycyclic aromatic hydrocarbons (Table 5.1) are associated with the use and combustion of fossil fuels (e.g., oil and gas) and other organic materials (e.g., wood). Natural sources of PAHs include forest fires and volca-

Table 5.1. Chemical contaminants analyzed in the sediment and coral tissues collected in Vieques.

PAHs - Low Molecular Weight	PAHs - High Molecular Weight	Organochlorine Pesticides	PCBs	Trace and Major Elements
Naphthalene	Fluoranthene	Aldrin	PCB8/5	Aluminum (Al)
1-Methylnaphthalene	Pyrene	Dieldrin	PCB18	Antimony (Sb)
2-Methylnaphthalene	C1-Fluoranthenes/Pyrenes	Endrin	PCB28	Arsenic (As)
2,6-Dimethylnaphthalene	C2-Fluoranthenes/Pyrenes	Heptachlor	PCB29	Cadmium (Cd)
1,6,7-Trimethylnaphthalene	C3-Fluoranthenes/Pyrenes	Heptachlor-Epoxide	PCB31	Chromium (Cr)
C1-Naphthalenes	Naphthobenzothiophene	Oxychlordane	PCB44	Copper (Cu)
C2-Naphthalenes	C1-Naphthobenzothiophenes	Alpha-Chlordane	PCB45	Iron (Fe)
C3-Naphthalenes	C2-Naphthobenzothiophenes	Gamma-Chlordane	PCB49	Lead (Pb)
C4-Naphthalenes	C3-Naphthobenzothiophenes	Trans-Nonachlor	PCB52	Manganese (Mn)
Benzothiophene[1]	Benz[a]anthracene	Cis-Nonachlor	PCB56/60	Mercury (Hg)
C1-Benzothiophenes[1]	Chrysene	Alpha-HCH	PCB66	Nickel (Ni)
C2-Benzothiophenes[1]	C1-Chrysenes	Beta-HCH	PCB70	Selenium (Se)
C3-Benzothiophenes[1]	C2-Chrysenes	Delta-HCH	PCB74/61	Silicon (Si)
Biphenyl	C3-Chrysenes	Gamma-HCH	PCB87/115	Silver (Ag)
Acenaphthylene	C4-Chrysenes	DDMU	PCB95	Tin (Sn)
Acenaphthene	Benzo[b]fluoranthene	2,4'-DDD	PCB99	Zinc (Zn)
Dibenzofuran	Benzo[k]fluoranthene	4,4'-DDD	PCB101/90	
Fluorene	Benzo[e]pyrene	2,4'-DDE	PCB105	**Energetics[2]**
C1-Fluorenes	Benzo[a]pyrene	4,4'-DDE	PCB110/77	
C2-Fluorenes	Perylene	2,4'-DDT	PCB118	1,3,5-Trinitrobenzene
C3-Fluorenes	Indeno[1,2,3-c,d]pyrene	4,4'-DDT	PCB128	1,3-Dinitrobenzene
Anthracene	Dibenzo[a,h]anthracene	1,2,3,4-Tetrachlorobenzene	PCB138/160	2,4,6-Trinitrotoluene
Phenanthrene	C1-Dibenzo[a,h]anthracenes	1,2,4,5-Tetrachlorobenzene	PCB146	2,4-Dinitrotoluene
1-Methylphenanthrene	C2-Dibenzo[a,h]anthracenes	Hexachlorobenzene	PCB149/123	2,6-Dinitrotoluene
C1-Phenanthrene/Anthracenes	C3-Dibenzo[a,h]anthracenes	Pentachloroanisole	PCB151	2-Amino-4,6-dinitrotoluene
C2-Phenanthrene/Anthracenes	Benzo[g,h,i]perylene	Pentachlorobenzene	PCB153/132	2-Nitrotoluene
C3-Phenanthrene/Anthracenes		Endosulfan II	PCB156/171/202	3-Nitrotoluene
C4-Phenanthrene/Anthracenes	**Butyltins**	Endosulfan I	PCB158	4-Amino-2,6-dinitrotoluene
Dibenzothiophene		Endosulfan Sulfate	PCB170/190	4-Nitrotoluene
C1-Dibenzothiophenes[1]	Monobutyltin	Mirex	PCB174	HMX
C2-Dibenzothiophenes[1]	Dibutyltin	Chlorpyrifos	PCB180	Nitrobenzene
C3-Dibenzothiophenes[1]	Tributyltin		PCB183	RDX
	Tetrabutyltin		PCB187	TETRYL
			PCB194	Perchlorate
			PCB195/208	
			PCB201/157/173	
			PCB206	
			PCB209	

[1]The benzothiophenes and dibenzothiophenes are thio-PAHs; [2]energetics not analyzed in coral tissues.
Abbreviations: PAHs, polycyclic aromatic hydrocarbons; HCH, hexachlorocyclohexane; DDT, dichlorodiphenyltrichloroethane; DDD, dichlorodiphenyldichloroethane; DDE, dichlorodiphenyldichloroethylene; DDMU, 1-chloro-2,2- (p-chlorophenyl)ethylene; PCB, polychlorinated biphenyl; HMX, cyclotetramethylene tetranitramine; RDX, cyclotrimethylene trinitramine

Table 5.2. Structure of selected organic compounds.

Compound Class	Compound	Structure	Use
Polycyclic aromatic hydrocarbon (PAH)	Benzo[a]pyrene		Byproduct of use and combustion of fossil fuels
Polychlorinated biphenyl	2,2', 5,5'-Tetra chlorinated biphenyl		Former widespread use in transformers, capacitors and hydraulic and heat transfer applications
Organochlorine pesticide	DDT		Insecticide, banned in US in 1972
Butyltin	Tributyltin (TBT) (X = anion or anionic group)		Biocide; banned on smaller vessels (<25 m) in the US in 1988

noes. The PAHs analyzed are two to six ring aromatic compounds. An example of the structure of PAHs can be seen in Table 5.2. PAHs were analyzed using gas chromatography/mass spectrometry in the selected ion monitoring (SIM) mode.

Effects of PAHs. An extensive amount of research on the accumulation and effects of PAHs has been conducted on aquatic organisms, however, very little research has been carried out to address the effects of PAHs on corals. Because of their hydrophobic nature, PAHs readily accumulate in marine organisms through the body surface, gills, or through the diet (Neff 1985). Exposure to PAHs has been associated with oxidative stress, effects on the immune system and endocrine system, and developmental abnormalities (Hylland 2006). In addition, a number of PAHs including benzo[a]pyrene, benz[a]anthracene, chrysene, benzo[b]fluoranthene, benzo[k]fluoranthene, dibenzo[a,h]anthracene, and indeno[1,2,3-c,d]pyrene are likely carcinogens (USDHHS 1995). The carcinogenic potential of PAHs is associated with their metabolism by Phase I P450 enzymes, generating reactive epoxides which can bind to cellular components such as DNA (Hylland 2006; Neff 1985).

In addition to the living tissues of corals, PAHs can also accumulate in the zooxanthellae, the symbiotic photosynthetic dinoflagellate algae found within coral tissues. Bioaccumulation appears to be related to the lipid content of both (Kennedy et al. 1992). While the simple accumulation of PAHs by corals is not an impact by itself, the accumulation of a chemical contaminant in an organism increases the likelihood of adverse effects. Solbakken et al. (1984) showed that both phenanthrene and naphthalene were accumulated by the brain coral *Diploria strigosa* and green cactus coral *Madracis decatis*, and that the lower molecular weight naphthalene was eliminated at a higher rate than phenanthrene (Solbakken et al. 1984). The PAHs fluoranthene and pyrene have been shown to be toxic to adult corals, particularly in the presence of increased ultraviolet radiation (phototoxicity) (Peachey and Crosby 1996; Guzman-Martinez et al. 2007).

PCBs

Polychlorinated biphenyls are a class of synthetic compounds that have been used in numerous applications ranging from electrical transformers and capacitors, to hydraulic and heat transfer fluids, to pesticides and paints. Although no longer manufactured in the U.S., environmental contamination by PCBs is widespread due to their environmental persistence and tendency to bioaccumulate. In some cases, use of PCB containing equipment (e.g., railroad locomotive transformers) is still permitted (CFR 1998). PCBs have a biphenyl ring structure (two benzene rings with a carbon to carbon bond) and a varying number of chlorine atoms (Table 5.2). There are 209 PCB congeners (structures) possible. PCBs were analyzed using gas chromatography/electron capture detection.

Effects of PCBs. Exposure to PCBs in fish has been linked to reduced growth, reproductive impairment and vertebral abnormalities (EPA 1997). Solbakken et al. (1984) investigated the bioconcentration of radiolabeled hexaPCB (2,4,5,2',4',5'-hexachlorobiphenyl) in coral. The PCB was rapidly accumulated in *Diploria strigosa* and *Madracis decatis*, however, depuration proceeded at a slow rate; after 275 days nearly 33 percent of the original radioactivity from the PCB remained in the coral.

Organochlorine Pesticides

A total of 31 organochlorine pesticides and related compounds were analyzed in the sediment and coral samples from Vieques (Table 5.1). Beginning in the 1950s and continuing to the early 1970s, a series of chlorine-containing hydrocarbon insecticides were used to control mosquitoes and agricultural pests. One of the best known of the organochlorine pesticides used during this time period was DDT. It has been estimated that during the 30 years prior to its cancellation in 1972, 1.35 billion pounds of DDT were applied in the US, with the majority applied to the cotton crop (EPA 2009). The use of many of the organochlorine pesticides, including DDT, was banned due to their environmental persistence, potential to bioaccumulate, and toxicity to nontarget organisms. From Table 5.2, it can be seen that some of the organochlorine compounds, including DDT, share structural similarities to PCBs, which are also persistent environmental contaminants (Table 5.2). Because of their persistence and heavy use in the past, residues of many organochlorine pesticides can be found in the environment, including biota.

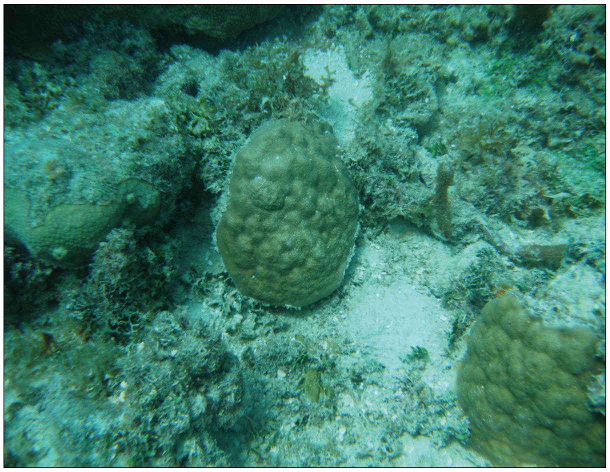


Image 5.3. Encrusting form of *Porites astreoides*, similar to the size of the colonies sampled. Diameter of colony shown is approximately 25 cm.

Effects of Organochlorine Pesticides. Organochlorine pesticides are typically neurotoxins. Both DDT and PCBs have also been shown to interfere with the endocrine system. DDT and its metabolite DDE were specifically linked to eggshell thinning in birds, particularly raptors. A number of organochlorine pesticides are also toxic to aquatic life including crayfish, shrimp and some species of fish.

Butyltins

This class of compounds has a range of uses from biocides to catalysts to glass coatings. In the 1950s, tributyltin or TBT was first shown to have biocidal properties (Bennett 1996). Beginning in the late 1960s, TBT (Table 5.2) was incorporated into a very effective antifoulant paint system, quickly becoming one of the most effective paints ever used on boat hulls (Birchenough et al. 2002). TBT was incorporated into a polymer paint system that released the biocide at a constant and minimal rate, to control fouling organisms such as barnacles, mussels, weeds, and algae (Bennett 1996). In the aquatic environment, TBT is degraded by microorganisms and sunlight (Bennett 1996). The transformation involves sequential debutylization resulting in dibutyltin, monobutyltin, and finally inorganic tin (Batley 1996). Experiments have shown that the half-life of TBT, the amount of time needed to convert half of the TBT to dibutyltin in natural water samples, is on the order of days; degradation to monobutyltin takes approximately a month (Batley 1996). Experiments with aerobic sediments have shown that the half-life of TBT is similar to that measured in solution. In deeper, anoxic sediments, however, the half-life of TBT is considerably longer, on the order of 2 - 4 years (Batley 1996). Butyltins were analyzed using gas chromatography/flame photometric detection.

Effects of TBT. The widespread use of TBT as an antifouling agent was associated with endocrine disruption, specifically an imposex condition in marine gastropod mollusks. Beginning in 1989 in the U.S., the use of TBT as an antifouling agent was banned on vessels smaller than 25 m in length (Gibbs and Bryan 1996). Negri et al. (2002) investigated the effects of TBT in sediments from a shipwreck, on the coral *Acropora microphthalma* from the Great Barrier Reef in Australia. Sediments originally contained approximately 160 µg/g TBT. When diluted to 5 percent of the original concentration, successful settlement of coral larvae in the laboratory was prevented.

Major and Trace Elements

A total of 16 trace and major elements were measured in sediments, and 14 in coral tissues for this project (Table 5.1). Most of these elements are metals, however, antimony, arsenic and silicon are metalloids; selenium is a nonmetal. All occur naturally to some extent in the environment. Aluminum, iron, and silicon are major components of the Earth's crust. Some trace and major elements in the appropriate concentrations are biologically essential. As their name implies, trace elements such as chromium, cadmium, lead and nickel occur at lower concentrations in crustal material, however mining and manufacturing processes along with the use and disposal of products containing trace elements result in elevated concentrations in the environment. As mentioned earlier, a stratified random sampling design was used for this project in order to characterize the areas sampled. Using this approach all nearshore and lagoon areas had an equal chance of being selected for contaminant characterization. As a result, no samples were specifically collected to represent background conditions in these areas. Silver, cadmium, copper, lead, antimony, and tin were analyzed using inductively coupled plasma - mass spectrometry. Aluminum, arsenic, chromium, iron, manganese, nickel, silicon and zinc were analyzed using inductively coupled plasma - optical emission spectrometry. Mercury was analyzed using cold vapor - atomic absorption spectrometry. Selenium was analyzed using atomic fluorescence spectrometry. Total metal was analyzed for this project.

Effects of Trace Elements. A number of trace elements are toxic at low concentrations. Cadmium, used in metal plating, solders, and batteries has been shown to impair development and reproduction in several invertebrate species, and the ability to osmoregulate in herring larvae (USDHHS 1999; Eisler 1985). Mercury is volatile and can enter the atmosphere through processes including mining, manufacturing, combustion of coal, and volcanic eruptions. Effects of mercury on copepods include reduced growth and reproductive rates (Eisler 1987). Chromium has been shown to reduce survival and fecundity in the cladoceran *Daphnia magna*, and reduced growth in fingerling chinook salmon (*Oncorhynchus tshawytscha*) (Eisler 1986). Copper has a number of uses such as in antifouling paints, wood preservatives, heat exchangers in power plants, electrical wires, coinage, and agriculture. Although an essential element, elevated levels of copper can impact aquatic organisms, including reproduction and development in mysid shrimp (Eisler 1998). In corals, Reichelt-Brushett and Harrison (2005) found that a copper concentration of 20 µg/L significantly reduced fertilization success in brain coral *Goniastrea aspera*. At copper concentrations at or above 75 µg/L, fertilization success was one percent or less. Fertilization success was also significantly reduced in the coral *Acropora longicyathus* at 24 µg/L, similar to *G. aspera*.

Energetics

Fifteen energetics and related compounds (Table 5.1) were analyzed in the sediments collected from Vieques. There are three major classes of energetics used by the U.S. military, and include nitroaromatics such as TNT and trinitrobenzene, nitramines such as RDX and HMX, and the nitrate esters such as nitroglycerin (GlobalSecurity 2008). The energetics were analyzed in sediment samples from Vieques using high performance liquid chromatography (HPLC) with a UV (ultraviolet) detector (EPA Method 8330). Fourteen samples with energetics concentrations that appeared to be above the method detection level (MDL) were subsequently reanalyzed using EPA Method 8330, followed by LC/MS/MS (liquid chromatography/mass spectrometry/mass spectrometry) to confirm their presence.

Effects of Energetics. A number of studies have assessed the toxicity and accumulation of energetics. Rosen and Lotufo (2007) investigated the toxicity of TNT, RDX and HMX on the marine mussel *Mytilus galloprovincialis*. The effective concentration (EC50) of TNT that resulted in abnormal larval development in 50 percent of the test organisms was 750 µg/L. The highest concentrations of RDX (28,400 µg/L) and HMX (1,900 µg/L) tested failed to have any toxicological effects on the larvae. Lotufo and Lydy (2005) calculated kinetic bioconcentration factors in juvenile sheepshead minnows (*Cyprinodon variegatus*) for TNT (9.6 ml g^{-1}), RDX (1.7 ml g^{-1}) and HMX (0.5 ml g^{-1}).

Rosen and Lotufo (2005) investigated the toxicity and fate of TNT and RDX on the estuarine amphipod *Eohaustorius estuarius*. Sediments were spiked with ^{14}C-labeled TNT or nonradiolabeled RDX in ten day spiked sediment exposures. The LC_{50} for TNT ranged between 28 - 36 µg/g, depending on the sediment used in the test. The TNT critical body residues (tissue concentration associated with mortality) for *E. estuarius* ranged between 1.1 and 9.8 µg/g. Exposure to RDX did not result in significant mortality even at the highest measured sediment concentration of 2,400 µg/g dry weight, and tissue concentrations of 21 µg/g wet weight. Rosen and Lotufo (2005) noted that the lack of RDX lethal effects appeared consistent with results for other invertebrates.

TOC and Grain Size

Total organic carbon (TOC) and grain size analyses were also carried out on the sediment samples. These two characterizations are important for assessing the potential for accumulation of contaminants in sediments. Typically, a positive relationship exists between sediment TOC and chemical contaminants, particularly organic contaminants, in freshwater, estuarine and coastal waters (Shine and Wallace 2000; Hassett et al. 1980). TOC was quantified in the sediments using a sequence of steps that involves combusting the carbon in a sample at a high temperature and then quantifying the CO_2 produced. Grain size is also an important sediment characteristic as many organic contaminants and a number of metals bind to the smaller silt and clay grain size fractions of sediments, due to the larger surface areas of these fractions, and in the case of trace and major elements, the charge characteristics of clays. Grain size analysis was carried out using a series of sieving and settling techniques. Additional information on TOC and grain size analysis can be found in McDonald et al. (2006).

Radioactivity

As part of the sediment collections in the inland lagoons, a reading of radioactivity (i.e., alpha, beta, and gamma radiation) was made using a Radalert 100 ™ nuclear radiation monitor. Readings were made at each site before a sediment sample was taken, and then again by holding the radiation monitor within 5 cm of the collected sediment sample. Readings were taken in milliroentgens per hour (mR/hr).

Clostridium perfringens

Although not a chemical contaminant, the bacterium *Clostridium perfringens* has been used as an indicator of fecal pollution and was analyzed in the sediment samples from Vieques. This bacterium occurs in the intestines of humans and in some domestic and feral animals, and ingestion of *C. perfringens* can cause food poisoning. For this analysis, sediment extracts were plated on a specialized growth medium and then incubated anaerobically for 48 hours, after which time the *C. perfringens* colonies were counted.

Statistical Analyses

All contaminant data were analyzed using JMP® statistical software. A Shapiro-Wilk test was first run on individual parameters to see if the data were normally distributed. When data were normally distributed, an analysis of variance (ANOVA) and Tukey HSD were calculated to explore relationships between parameters. If the data were not normally distributed and a log10 data transformation was not effective, Wilcoxon or Spearman's nonparametric tests were used. Some contaminant data that were not normally distributed were subsequently ranked to allow ANOVAs and pair-wise comparisons. All statistical tests used an alpha value of 0.05.

5.3 PREVIOUS STUDIES

A significant amount of work has been conducted over the years to assess chemical contaminants in Vieques, primarily in the areas formerly owned by the U.S. Navy, with much of this work occurring in the terrestrial environment. A number of studies have been completed, while others are ongoing. To better understand the chemical contaminant issues that might be present in Vieques, and to put the current work into perspective, a literature survey was carried out for previous contaminant-related research in the terrestrial and nearshore environments. Previous studies of contaminants on or near the island of Vieques include assessments of metals, energetics, volatile organic compounds, pesticides, PCBs and other contaminants. The majority of these assessments characterize chemical contaminants in soil samples, but a number of studies also include the analysis of fish and shellfish, terrestrial plant materials, surface and subsurface land-based water samples, air samples and sediment samples from limited marine locations.

Studies Conducted

One of the earlier assessments was conducted in 1972 by the U.S. Geological Survey to evaluate the metallic resources of Vieques (Learned et al. 1973). In a study commissioned by the U.S. Navy, soil samples from the Eastern Maneuver Area (EMA) and Live Impact Area (LIA) were collected to characterize the presence of explosive compounds (Lai 1978; Hoffsommer and Glover 1978). In the last decade, numerous studies also commissioned by the U.S. Navy have been carried out, with the majority conducted by the Agency for Toxic

Substances and Disease Registry (ATSDR) and CH2MHILL (ATSDR 2001, 2003a, 2003b, 2003c; CH2MHILL 2000, 2001, 2004, 2007; CH2MHILL and Baker 1999). The focus of most of these studies included the former Live Impact Area (LIA), Eastern Maneuver Area (EMA), and the solid waste management units (SWMU) and areas of concern (AOCs) on the western end of the island (NASD).

Findings. Elevated levels of trace elements have been documented in both the former Vieques Naval Training Range (VNTR) and in the municipal regions of Vieques (ATSDR 2003b; NOAA and Ridolfi, 2006). The higher concentrations of trace elements were found in areas on or nearshore of the former LIA and the NASD. It should be noted, however, that most of the studies that have been conducted appear to have concentrated on the areas formerly owned by the U.S. Navy.

CH2MHILL (2007) conducted a survey of soil inorganics (e.g., trace and major elements) for East Vieques. The goal of the survey was to establish background levels within the former VNTR which could then be used to assess whether site-specific concentrations could be attributable to releases from these sites, or were more consistent with background levels. For each element, a UTL or Upper Tolerance Level was developed. Elemental concentrations at or below the UTL threshold concentration represent those levels that are indistinguishable from background concentrations. Not surprisingly, the UTLs were highest for major elements including aluminum (35,000 µg/g), iron (38,100 - 43,200 µg/g) and magnesium (3,710 - 22,200 µg/g) for various soil types on Vieques. For the trace elements, the arsenic UTLs ranged from 1.6 - 9.2 µg/g; for cadmium 2.2 to 2.4 µg/g, chromium 70-72 µg/g, lead 5.4 - 16 µg/g, copper 53-94 µg/g, nickel 22 - 41 µg/g, and mercury 0.057 - 0.31 µg/g.

The highest concentrations of trace elements were found in or nearshore of the former LIA, and are noted in Figure 5.3. The highest trace element levels detected include arsenic (42.2 µg/g in sediments), cadmium (46.8 µg/g in coral tissues), chromium (182.6 µg/g in plant organic material), lead (195 µg/g in coral tissues), manganese (1,740 µg/g in plant organic material), mercury (< 2.15 µg/g in sediments), nickel (78.3 µg/g in plant organic material), and selenium (11 µg/g in lobster tissues) (ATSDR 2006; Barton and Porter 2004; CH2MHILL 2002; Massol-Deya et al. 2005; NOAA and Ridolfi 2006). The highest concentrations for the five remaining elements were all found on the Western end of Vieques on or near the former NASD. These metals include aluminum (1,250 µg/g) in fiddler crab (*Uca sp.*) tissues, copper (203 µg/g) in fiddler crab (*Uca sp.*), iron (39,000 µg/g) in soils, magnesium (16,000 µg/g) in soils, and zinc (97 µg/g) in fiddler crab (*Uca sp.*) tissues (ATSDR 2006; Barton and Porter 2004; CH2MHILL 2002; Massol-Deya et al. 2005; NOAA and Ridolfi 2006).

The presence of 17 organochlorine pesticides in Vieques has been documented in the tissues of land crabs (*Cardisoma guanhumi*) (Lopez 2002; NOAA and Ridolfi 2006). The majority of the detections were for DDT or one of its metabolites, while chlordane was found at approximately 50% of the sites sampled (NOAA and Ridolfi 2006). Other pesticides detected include Mirex, endosulfan sulfate, methoxychlor, and aldrin. The highest concentration detected for an organochlorine pesticide was DDT in *C. guanhumi* (203.2 ng/g) from Laguna Kiani on the western end of Vieques (NOAA and Ridolfi 2006). The second highest DDT concentration (187.2 ng/g) was found near the public vehicle access bridge near Red Beach (NOAA and Ridolfi 2006).

Commercial PCB products used in the U.S. were referred to as Aroclors, and are mixtures of PCB congeners. For example, Aroclor 1242 refers to a mixture of PCBs that is 42 percent chlorine by weight. Nine PCB Aroclors (1016, 1221, 1232, 1242, 1248, 1254, 1260, 1262, and 1268) were analyzed in the tissues of fiddler crabs (*Uca sp.*) and land crabs (*C. guanhumi*) from Vieques (NOAA and Ridolfi 2006). In only one of the samples were PCBs detected. The fiddler crab sample was collected near Laguna Kiani and had an Aroclor 1254 concentration of 58 ng/g (NOAA and Ridolfi 2006), substantially below the EPA ecological screening benchmark of 23 ug/g. The ATSDR (2006) concluded that the levels of PCBs found in land crabs by NOAA and Ridolfi (2006) were lower than levels reported in the scientific literature as causing harmful human health effects.

Energetics have occasionally been detected in the terrestrial and marine environments of Vieques (ATSDR 2003a,b; Barton and Porter 2004). HMX (cyclotetramethylene tetranitramine) (0.42 µg/g), RDX (cyclotrimethylene trinitramine) (2.8 µg/g), TNT (2,4,6-trinitrotoluene) (13 µg/g), nitroglycerin (19 µg/g), and 2-amino-4,6-dinitrotoluene (degradation product of TNT) (0.62 µg/g) have been detected in soil samples from the former LIA (ATSDR 2003a). In the marine environment, Barton and Porter (2004) investigated the presence of explosives adjacent to the scuttled Navy ship *USS Killen*. TNT was detected at a concentration of 4,380 µg/g adjacent (less than 2 meters) to a 2,000 pound bomb at the site, and 19,333 µg/g TNT inside the bomb. Concentrations of TNT rapidly decreased to levels below detection at distances greater than 2 meters from the bomb (Barton and Porter 2004). TNT and RDX were not detected in the sediments at the bow or stern of the ship, suggest-

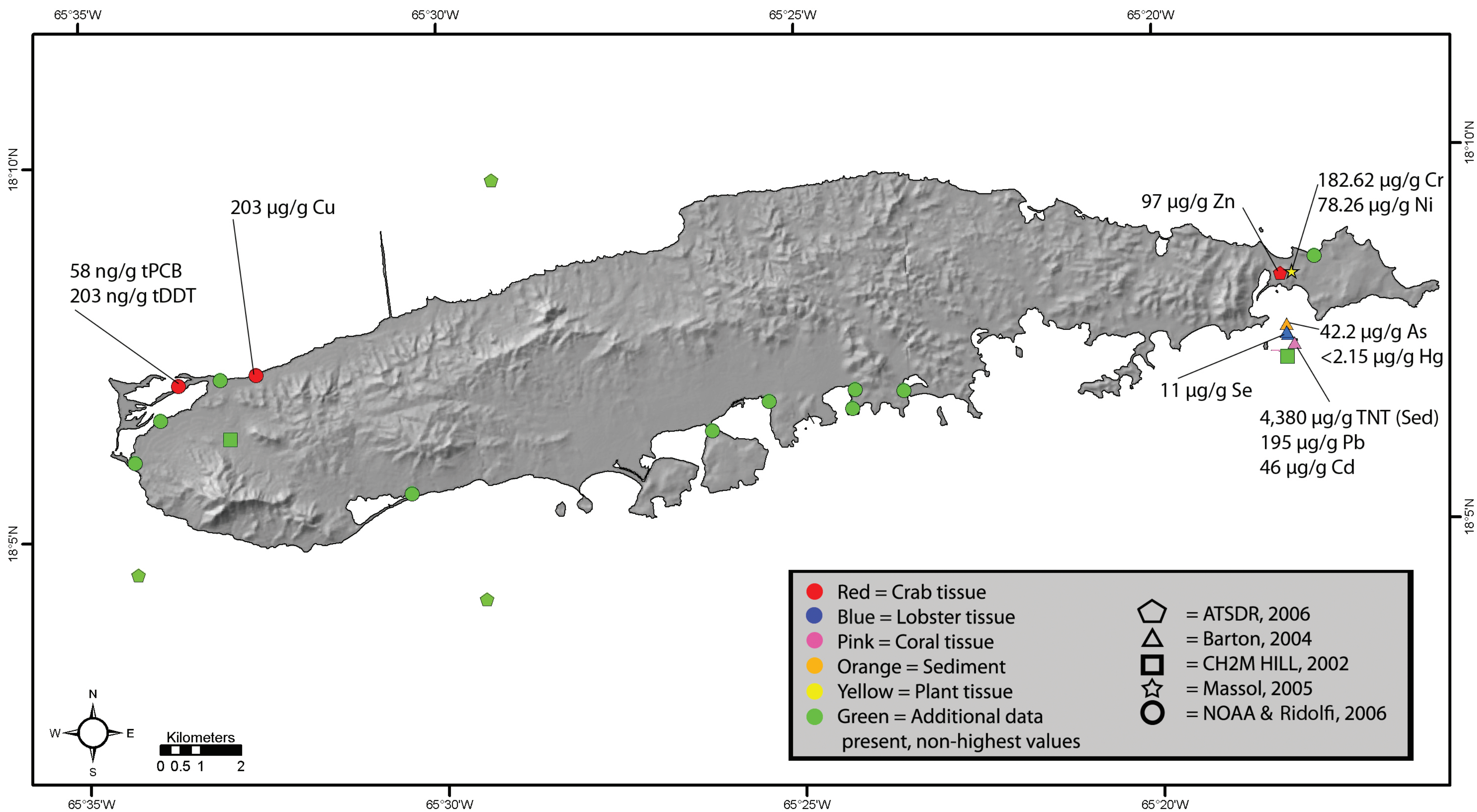


Figure 5.3. Sites of previous contaminant-related studies on Vieques.

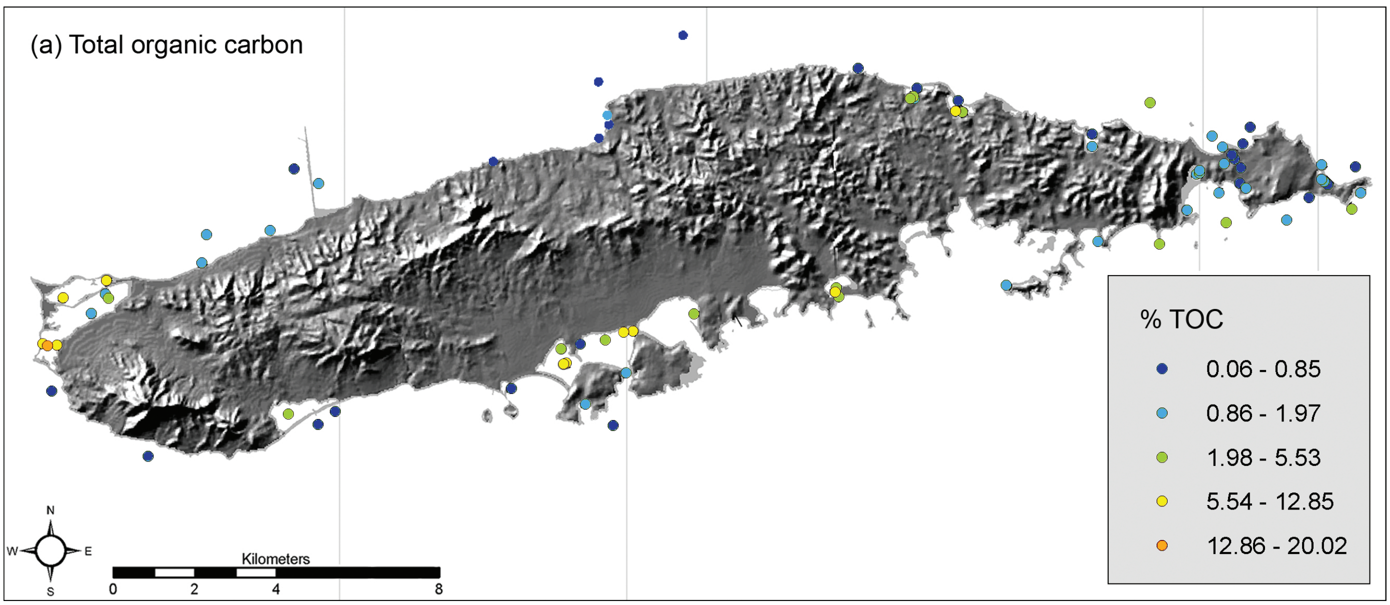
ing that the presence of higher concentrations of energetics may be a localized phenomenon (i.e., in direct proximity to unexploded ordnance). TNT was also detected at a concentration of 252 μg/g in one coral (*Diploria labyrinthiformis*) sample adjacent to the stern of the scuttled ship.

5.4 RESULTS AND DISCUSSION

All Appendices cited in this section are available online at http://ccma.nos.noaa.gov/ecosystems/coralreef/vieques.html.

Field Data

The average water depth of the non-inland lagoon sediment sites in Vieques was 4.5 ± 0.7 m; the average surface water temperature was 29.6 ± 0.2 ºC, and the average bottom temperature was 29.2 ± 0.1 ºC. The salinity at the non-inland lagoon sites was also fairly constant. The average surface salinity was 35.6 ± 0.5 ppt, the average bottom salinity was 35.9 ± 0.7 ppt. These data indicated no stratification for either temperature or salinity. The dissolved oxygen at the non-inland lagoon sites was 5.4 ± 0.4 mg/L near the surface; 6.3 ± 0.3



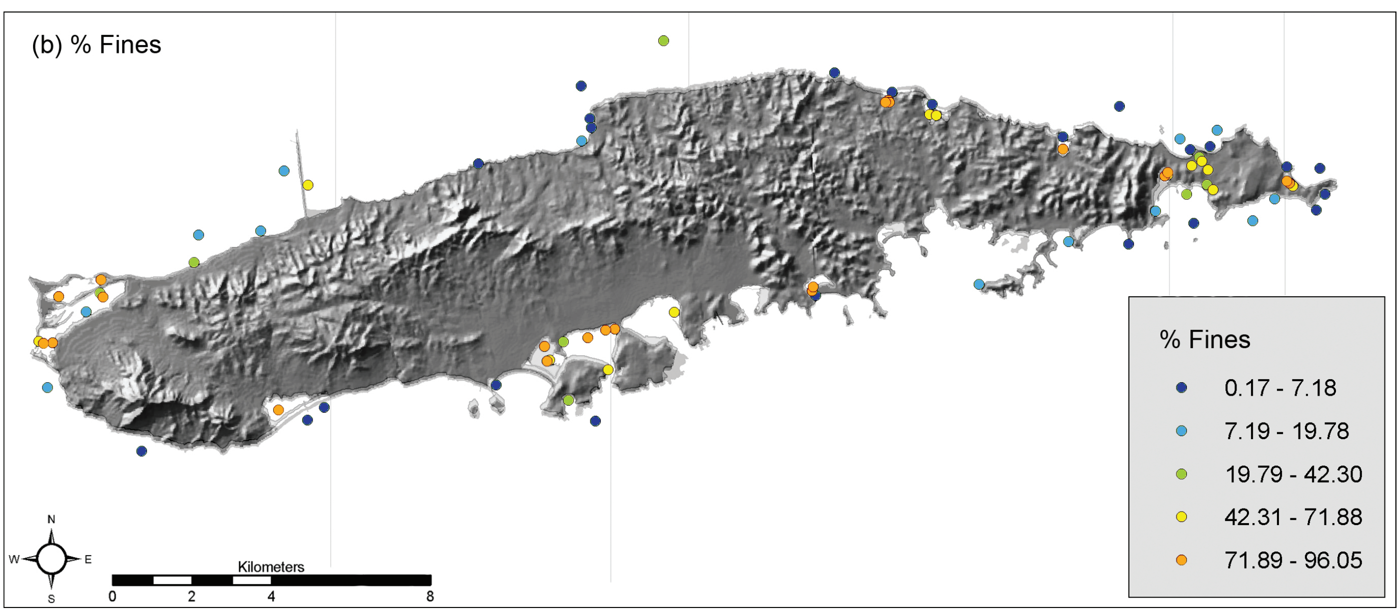


Figure 5.4. Total organic carbon (TOC) (a) and % fines (b) in sediments. Fines is the sum of the % silt and % clay fractions of the sediments.

mg/L near the bottom. It is unclear why the mean dissolved oxygen appeared higher near the bottom, as there was little evidence of stratification in terms of temperature. One possible explanation could be benthic primary production.

The inland lagoons were shallower with more variability in the water parameters measured. The average temperature at the inland lagoon sites was 33.0 ± 0.4 ºC. The salinity ranged from 4.8 to 79.2 ppt, with an average of 37.8 ± 3.2 ppt. The mean dissolved oxygen level in the inland lagoons was 4.3 ± 0.5 mg/L. The detailed field data collected during May 2007 (sediment and coral sites, and some inland lagoon sites) and October 2007 (inland lagoon sites) can be found in Appendix A and B, respectively. Equipment failure prevented the measurement of water parameters at some of the sites where sediments or coral tissues were sampled.

Sediment Total Organic Carbon (TOC)

Chemical contaminants, particularly organics (i.e., carbon-containing contaminants such as PCBs), tend to accumulate in sediments that have a higher organic carbon content, due to the binding of the contaminant to the organic carbon matrix on and within the sediment particles. The relationship between TOC and organic contaminants is fairly common and has been found in freshwater, estuarine and coastal systems. Because of this correlation, organic contaminant concentrations are sometimes normalized to the organic carbon content of sediments (Shine and Wallace 2000; Hassett et al. 1980). Figure 5.4a summarizes TOC in the sediments analyzed from Vieques. The average sediment TOC was 2.49 ± 0.38%. Not surprisingly, higher TOC levels were found in nearshore and inland lagoon areas (Figure 5.4a), which are likely subjected to greater inputs of terrestrial organic matter. The average TOC in the inland lagoon areas was 4.25 ± 0.74%, compared with 1.05 ± 0.12% for the non-inland lagoon sites, and an ANOVA run on the log10 transformed data indicated this difference was significant ($p < 0.0001$).

The 95th percentile for TOC was 9.03%, and all sites within this quantile were from inland lagoons. The highest TOC (20.02%) found in any of the sediments analyzed was from 70S1P (Figure 5.4 and Figure 5.2) in Laguna Boca Quebrada, which is part of the SWMU4 (solid waste management unit) area in the western part of Vieques. The second highest was found at 07P, from the same lagoon. Sediments from the south side of the island also had higher TOC levels than those collected from the north side ($p = 0.0016$). Finally, there was a significant difference ($p = 0.0105$) between strata; North 2 and South 1 had significantly lower TOC concentrations than most of the other strata on the south side of the island.

Sediment Grain Size

The adsorption of contaminants, both organic and inorganic (e.g., trace elements) is also strongly influenced by the grain size of the sediment (Hassett et al. 1980). The smaller grain sizes of the silts and clays have proportionally higher surface areas available for adsorption. The adsorption of metals is influenced not only by smaller grain sizes, but also by ionic forces (i.e., negative charge structure) within the layered structure of clays. In this report, the silt and clay fractions are combined (summed) and reported as % fines.

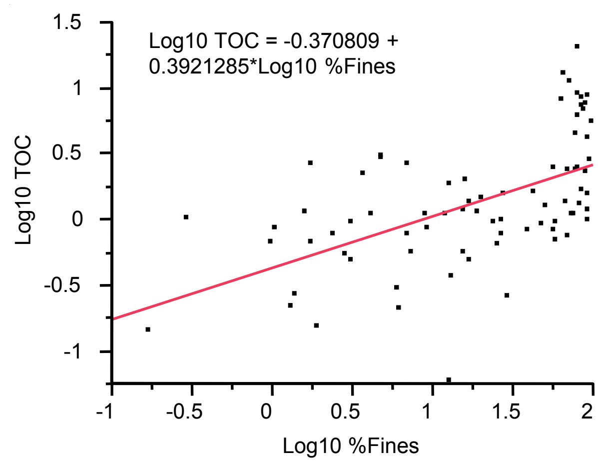


Figure 5.5. Bivariate fit of log10 normalized TOC and % fines for the sediment samples analyzed from Vieques.

The % fines in the sediments can be seen in Figure 5.4b. More detailed information on the results of the grain size analysis can be found in Appendix C. Like the TOC values, all of the sites containing fine grain sediments were from the nearshore and inland lagoon depositional areas. Areas containing finer grain sediments are important as these locations are more likely to accumulate contaminants if they are being introduced into the system. A Wilcoxon nonparametric test indicated a significant difference ($p < 0.0001$) in the % fines from inland lagoon areas versus non-lagoon areas, similar to that found for TOC. Finally, a positive relationship frequently exists between TOC and grain size. Higher TOC is usually associated with the silt fraction of sediments. Figure 5.5 shows a plot of log10 normalized concentrations of % fines and TOC content of the sediments in Vieques; the relationship was significant ($p < 0.0001$). Interestingly, although this relationship was found to be significant for the sediments collected throughout the coastal areas of the U.S. by the NS&T Program and in Vieques, this relationship did not hold for sediments collected in 2005 from southwest Puerto Rico (Pait et al. 2007).

Polycyclic Aromatic Hydrocarbons (PAHs)

The results of the PAH analysis in the sediments and corals can be seen in Figure 5.6 and also in Appendices D and F. The scale on the two graphics in Figure 5.6 is the same to better enable comparisons between sediments and corals. Total PAHs as used in this report refers to the sum of the 58 compounds and compound classes (e.g., anthracene, C1-naphthalenes, Table 5.1) analyzed.

PAHs in Sediments. The mean concentration of total PAHs in the sediments collected from Vieques was 52.3 ± 8.7 ng/g; the median was 17.9 ng/g. The higher concentrations of PAHs were found in sediments from the nearshore and inland lagoon areas (Figure 5.6a). Overall, the concentration of total PAHs in Vieques was low. Because of the long-term, national-level contaminant monitoring carried out by NOAA's NS&T Program, data from Vieques can be compared with data from the rest of the Nation's coastal waters. No sediment sites were above the national NS&T median of 395 ng/g for total PAHs, although 68S1P (370.3 ng/g) taken from Laguna Kiani in the northwestern portion of Vieques was near this value. Other higher total PAH concentrations found in the sediments in Vieques included 4N1P (287.7 ng/g) in Laguna El Pobre, 27N2A (283.9 ng/g) near the town of Isabel Segunda, 69S1P (276.5 ng/g) in Laguna Arenas, 46P (210.3 ng/g) along Blue Beach, and 70S1P (208.9 ng/g) in Laguna Boca Quebrada. Additional results can be found in Appendix D.

Comparisons Between Strata. A series of statistical tests were carried out to understand how the distribution of total PAHs in the sediments varied across the sites sampled on the island of Vieques. An ANOVA on the log10 normalized data indicated that the inland lagoons had significantly higher total PAH concentrations than nonlagoon areas ($p < 0.0001$). An ANOVA indicated no difference ($p = 0.1005$) in the concentration of sediment total PAHs between strata (e.g., North 5 versus South 1) There was also no difference in the concentration of total PAHs in the north strata versus the south strata ($p = 0.2540$). If the north and south strata are combined (e.g., North 1 and South 1), five strata (1 to 5) moving west to east across the island of Vieques result (Figure 5.7). This grouping can be used to compare contaminants in Vieques related to adjacent land use. When differences in total PAHs in sediments were assessed across these strata, an ANOVA indicated a significant difference ($p = 0.0130$), and a Tukey HSD showed that total PAHs in the far western Stratum 1 were significantly higher than in Stratum 4.

Summary for Total PAHs

- *The highest total PAH concentration in sediments was 370 ng/g and was found in Laguna Kiani in the western portion of Vieques (Stratum 1).*
- *Concentrations of total PAHs were higher in the inland lagoon areas of the island.*
- *Total PAHs in sediments were significantly higher in Lagoon 1 (Laguna Boca Quebrada); and in western Vieques.*
- *Overall, the concentrations of total PAHs in sediments were low; none of the concentrations of total PAHs exceeded the sediment quality guidelines examined.*
- *The concentration of total PAHs in coral (Porites astreoides) were not significantly different from the concentration in the sediments.*

Comparison Among Inland Lagoons. The October 2007 sediment sampling in Vieques focused on a number of inland lagoons, which enabled a comparison of contaminant concentrations between nine inland lagoons on the island (Figure 5.7). For total PAHs, an ANOVA on the log10 normalized total PAH values indicated a significant difference ($p = 0.0010$) between the nine lagoons sampled. A pairwise comparison (Tukey HSD) indicated that total PAHs in Lagoon 1 (Laguna Boca Quebrada) and 2 (Laguna Kiani) on the western side of Vieques were significantly higher than the concentration of total PAHs in sediments sampled from Lagoon 7 and 9.

Comparison with Sediment Quality Guidelines. The NS&T Program and others have developed effects-based, numeric guidelines to estimate the toxicological relevance of certain sediment contaminant concentrations (Long et al. 1998). Two of these guidelines, shown in Table 5.3, are the Effects Range-Low (ERL) and the Effects Range-Median (ERM) developed by NOAA, and define sediment contaminant concentration ranges that are rarely (< ERL), occasionally (ERL to ERM), or frequently (> ERM) associated with toxic effects in aquatic biota (typically amphipods) in the sediments (NOAA 1998). It can be seen from Table 5.3 that the concentration of total PAHs measured in the sediments in Vieques were substantially below the ERL (4,022 ng/g) and ERM (44,792 ng/g) values.

A number of other sediment quality guidelines have been developed to assess potential adverse effects from chemical contaminants in sediments. The Threshold Effects Level (TEL) and Probable Effects Level (PEL) are similar to the effects range approach (e.g., ERL), except that the TEL is the geometric mean of the 15th percentile of the effects data and 50th percentile of the no effects data (MacDonald et al. 1996). The PEL is the

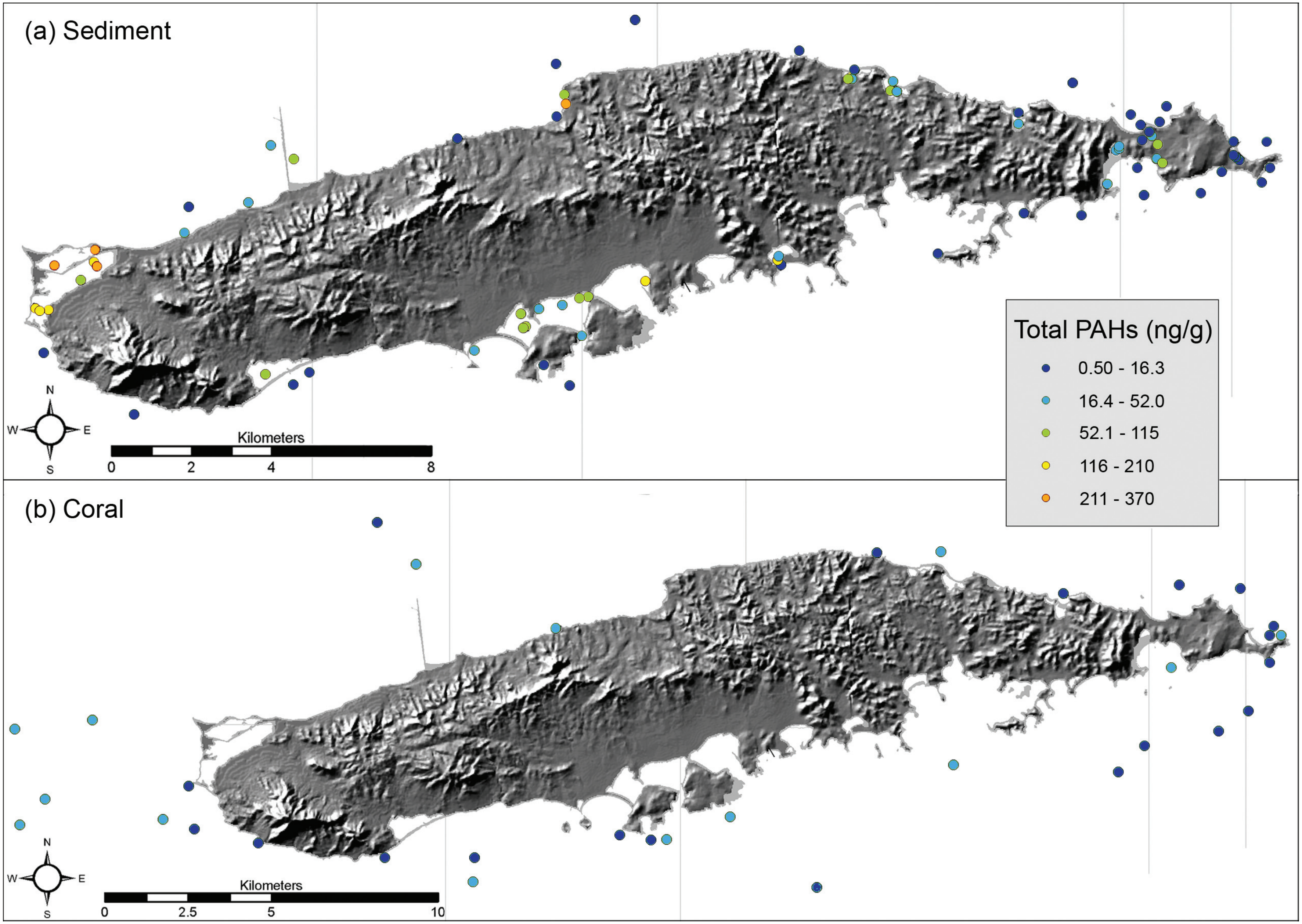


Figure 5.6. Total PAHs detected in the sediments (a) and in *Porites astreoides* (b).

geometric mean of the 50th percentile of the effects data and the 85th percentile of the no effects data. The Apparent Effects Threshold or AET, is used to help determine the concentration of a contaminant above which significant biological effects in benthic infaunal organisms could be expected (EPA 1989). AET values are determined using data on chemical contaminants and biological effects (from benthic infaunal analyses and from sediment bioassays) from contaminated and reference sites (EPA 1989).

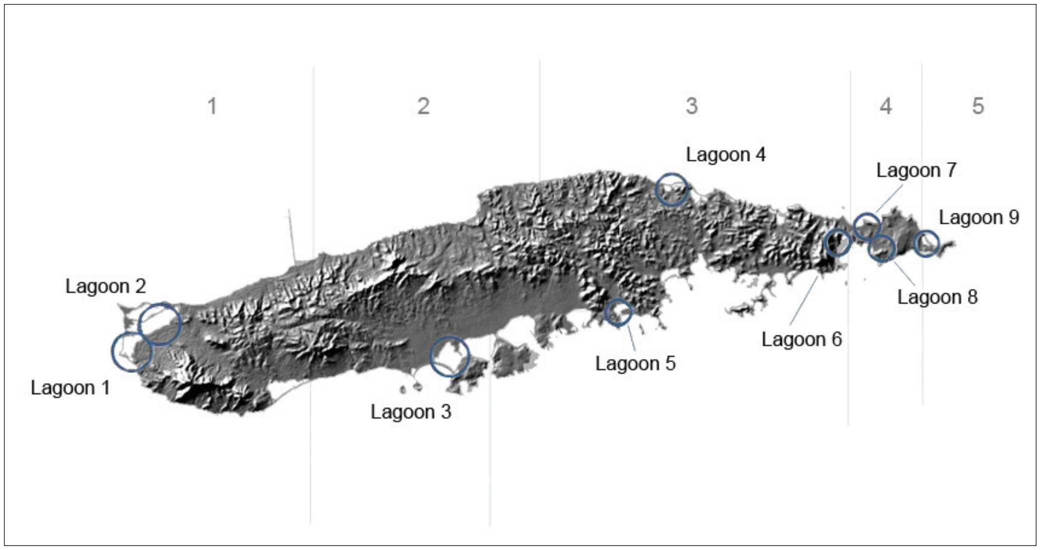


Figure 5.7. West to east strata (1 to 5) used to assess the influence of land-use patterns, and the nine inland lagoons where the sampling strategy allowed comparisons between lagoons.

Table 5.3 also contains the TEL and PEL values for total PAHs. It can be seen from this table that the mean and the highest total PAH values found in the sediments sampled were well below these guidelines. There are also a number of guidelines for individual PAHs. The only exceedance of one of the guidelines for individual PAHs was for dibenzo(a,h)anthracene. The TEL of 6.22 ng/g was exceeded at 19 sites (Appendix D). The highest dibenzo(a,h)anthracene concentration (29.3 ng/g) was found at 08P in Laguna Boca Quebrada (Figure 5.2).

The results for total PAHs found in the sediments can be compared with work recently completed in southwest Puerto Rico (Pait et al. 2007). In Vieques, the mean total PAH concentration in the sediments was 52.3 ng/g, similar to the mean total PAH concentration in southwest Puerto Rico, for sediments outside of Guanica Bay (48.1 ± 10.72 ng/g). Samples taken at the two sites in Guanica Bay for that project were somewhat elevated and if they are included, the mean total PAH concentration in sediments from the study area in southwest Puerto Rico was 80.6 ± 25.5 ng/g, higher than the mean sediment total PAHs found in Vieques.

Table 5.3. Total PAHs in Vieques sediments and guidelines.

Vieques Results	Concentration (ng/g)
Vieques sediment total PAHs minimum	0.5
Vieques sediment total PAHs maximum	370.3
Vieques sediment total PAHs mean	52.3 ± 8.7
Vieques sediment total PAHs median	17.9
NOAA NS&T	
Mean	3,390 ± 1,634
Median	395
85th Percentile	2,880
Guidelines	
Threshold Effects Limit (TEL)	1,684
Effects Range - Low (ERL)	4,022
Effects Range - Median (ERM)	44,792
Probable Effects Level (PEL)	16,770
Apparent Effects Threshold (AET)	NA

NA, not available

<u>PAHs and TOC.</u> The adsorption of organic contaminants onto sediments in many types of aquatic environments is strongly influenced by total organic carbon (Hassett et al. 1980; Shine and Wallace 2000). A bivariate regression (Figure 5.8a) of log10 normalized TOC against the concentration of log10 total PAHs in the sediments was significant ($p < 0.0001$).

<u>PAHs and Grain Size.</u> The adsorption of organic contaminants onto sediments is also strongly influenced by grain size (Hassett et al. 1980). The smaller grain sizes of the silts and clays have proportionally higher surface areas available for the adsorption of contaminants. A nonparametric analysis of nationwide data from the NS&T Program indicated a significant relationship between total PAH and % fines ($p < 0.001$). To assess the relationship for the samples collected in Vieques, a regression was run between % fines and the concentration of total PAHs in the sediments. The data for grain size and PAH concentration were log10 transformed. The bivariate regression (Figure 5.8b) of % fines against the concentration of total PAHs in the sediments was significant ($p < 0.0001$).

Normalization of PAHs to TOC and Fines. An exercise was carried out to normalize the concentration of total PAHs detected in the sediments to TOC (e.g., total PAH/TOC), and by % fines (e.g., total PAH/ % fines) across the study area. Normalizations of these types are used to help identify sources of contaminants (Birch 2003; Burgess et al. 2001). The normalization of nonpolar organic compounds is typically restricted to those sediments containing at least 0.2% TOC. Below 0.2%, other factors that influence the partitioning of contaminants (e.g., sorption to nonorganic mineral fractions) become relatively more important (Di Toro 1991). There were three samples (78S1A, 16N2P, and 37N3P) where the TOC was less than 0.2%. For these samples, the TOC was set at 0.2%. Because of the fairly low concentrations of total PAHs seen throughout the study area, the normalizations were not revealing, however, they are included in Appendix E.

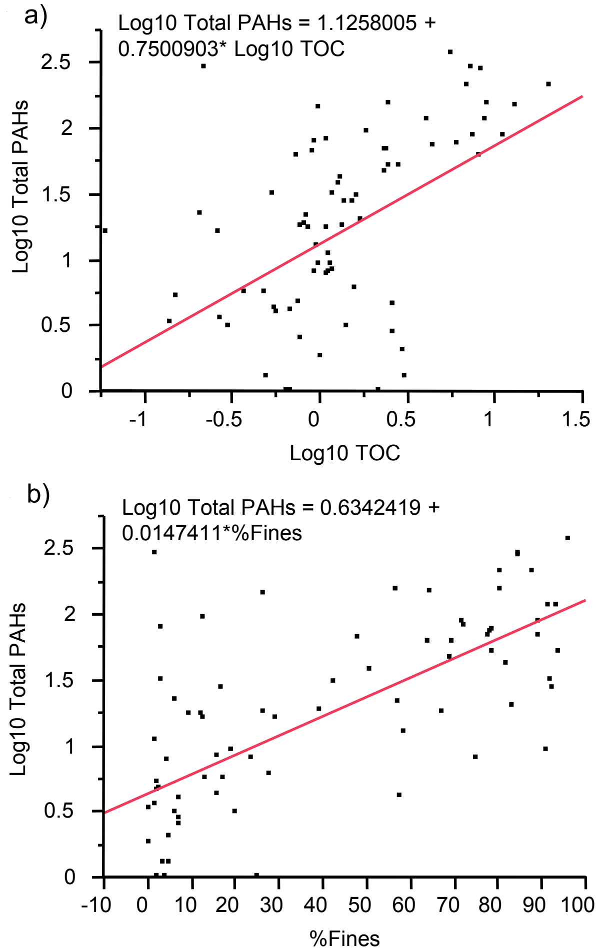


Figure 5.8. Bivariate fit of log10 total PAHs in sediments versus log10 TOC (a) and log10 % fines (b) from Vieques.

PAHs in Corals. The concentrations of total PAHs found in the coral tissues are presented in Figure 5.6b and in Appendix F. The mean concentrations of total PAHs in the tissues of *P. astreoides* (15.0 ± 0.6 ng/g) were numerically lower than that found in the sediments (52.3 ng/g), however, an ANOVA indicated that the difference was not significant (p = 0.6624). Pait et al. (in press) calculated a mean total PAH concentration of 46.9 ± 18.5 ng/g in *P. astreoides* from southwest Puerto Rico, somewhat higher than in corals from Vieques. Unfortunately, no guidelines appear to exist for any chemical contaminants in corals.

A number of ANOVAs were also carried out to assess how the distribution of total PAHs (log10 transformed) in the coral tissues varied across Vieques. The results indicate there was no difference in the concentration of total PAHs in the north strata versus the south strata (p = 0.5160), nor were there differences in the concentration of sediment total PAHs between strata (e.g., North 5 versus South 1) (p = 0.0900), or total PAHs in corals moving west to east (p = 0.1138) (Strata 1 to 5, Figure 5.7).

Normalization of Coral Tissues to Lipid Content. Just as sediments can be normalized to TOC, tissues can be normalized to lipid content, which can help identify possible sources of contaminants (Lake et al. 1990). The results of normalizing total PAHs by coral lipid content were not very revealing as concentrations of PAHs in coral tissues across Vieques were consistently low, but are included in Appendix G.

PAH Accumulation and Effects in Corals. Thomas and Li (2000) used supercritical extraction of ground and air dried samples of the coral *Porites compressa* followed by immunoaffinity chromatography, and analysis by gas chromatography and mass spectrometry to quantify PAHs present. Corals were collected at Kaneohe Bay in Oahu, Hawaii, which is impacted by industrial, military and civilian use in addition to wastewater discharges. Thomas and Li (2000) analyzed for a number of PAHs including fluorene, phenanthrene, anthracene, fluoranthene, pyrene, chrysene, benzo[e]pyrene, and benzo[a]pyrene. The total concentration for these PAHs in the coral (*P. compressa*) sampled from Kaneohe Bay was 220 ng/g, substantially higher than that found in *P. astreoides* in Vieques. Readman et al. (1996) analyzed for PAHs (including phenanthrene, fluoranthene, and pyrene) in the coral *Porites lutea* from Kuwait. In sections of the coral corresponding to the 1988/1989 timeframe (prior to the Gulf War), the concentration of these PAHs was approximately 0.3 ng/g. It should be noted, however, that Readman et al. (1996) sectioned and analyzed coral skeleton for PAHs.

Peachey and Crosby (1996) investigated the phototoxicity of PAHs. Phototoxicity refers to the toxic effects of chemicals caused or enhanced by light. In the laboratory, larvae of the coral *Fungia scutaria* (mushroom coral) were first exposed to nominal concentrations of pyrene ranging from 1 - 48 µg/L for a period of 2 hours. Larvae were then exposed to artificial sunlight and evaluated for changes in their mobility over a period of eight hours. A nominal pyrene concentration of 32 µg/L resulted in a significant number (40%) of immobilized larvae.

Guzman-Martinez et al. (2007) showed that the PAH fluoranthene at a concentration of 60 µg/L reduced photochemical efficiency in the coral *Porites divaricata* when combined with ultraviolet radiation at levels to simulate natural solar radiation, similar to the results found by Peachey and Crosby (1996). PAHs have also been shown to induce microsomal degradative enzymes (Cytochrome P450 class) in corals. As noted earlier P450 enzymes, particularly in higher organisms, can metabolize contaminants such as PAHs, often making them more water soluble, and enhancing their rate of excretion. Gassman and Kennedy (1992) were among the first researchers to show that at least some corals possess Cytochrome P450 enzymes. From these articles, it can be seen that PAHs can accumulate and impact corals. However, it should be noted that most of the contaminant effects data for corals are from dissolved concentrations in water. The concentration of contaminants in water (e.g., µg/L) having an effect cannot be directly compared with concentration in sediments (e.g., ng/g).

Polychlorinated Biphenyls (PCBs)

The results of the PCB analysis in sediments and coral tissues can be seen in Figure 5.9 and in Appendices H and J. The scale on the two graphics in Figure 5.9 is the same to make comparisons between sediments and corals easier. Total PCBs as used in this report was calculated using the following equation:

$$\text{Total PCBs} = (\text{sum of 18 PCB congeners} \times 2.19) + 2.19$$

The congeners used in the equation include: PCB8, PCB18, PCB28, PCB44, PCB52, PCB66, PCB101, PCB105, PCB118, PCB128, PCB138, PCB153, PCB170, PCB180, PCB187, PCB195, PCB206, and PCB209. The equation is used within the NS&T Program to estimate the total concentration of PCB congeners present in a sample (NOAA 1993).

PCBs in Sediments. The mean concentration of total PCBs in the sediments sampled in Vieques was 2.86 ± 0.14 ng/g; the median 2.38 ng/g (Table 5.4). The mean for total PCBs in sediments for 2006 and 2007 from the NS&T Program (most recent year of NS&T sediment data) is somewhat higher, 13.7 ± 2.70 ng/g. The higher concentrations of PCBs in Vieques tended to be found in sediments from the nearshore and inland lagoon areas (Figure 5.9a). The highest concentration of total PCBs (9.82 ng/g) in the sediments was from 38P (Figure 5.1) in Lagoon 6 in the North 4 stratum.

Summary for Total PCBs

- *The highest total PCB concentration in sediments was 9.82 ng/g and was found in Lagoon 6 adjacent to the former Live Impact Area (LIA).*
- *Concentrations of total PCBs were higher in the inland lagoons.*
- *There were no differences in total PCB concentrations in sediments between any of the strata.*
- *Overall, the concentrations of total PCBs in sediments were low; none of the concentrations of total PCBs exceeded the sediment quality guidelines examined.*
- *The concentration of total PCBs in coral (Porites astreoides) were not significantly different from the concentration in the sediments.*

The results for total PCBs found in the sediments can be compared with work recently completed in southwest Puerto Rico (Pait et al. 2007). The mean total PCB concentration in the sediments for those sites in southwest Puerto Rico outside of Guanica Bay was 18.1 ± 2.96 ng/g, higher than in Vieques. Samples taken at the two sites within Guanica Bay were elevated for a number of contaminants, including PCBs. If the two sites in Guanica Bay are included, the mean total PCBs concentration in sediments from the study area in southwest Puerto Rico was 104.1 ± 66.3 ng/g.

Comparisons Between Strata. As with the PAHs, a series of statistical analyses were carried out to understand how the distribution of total PCBs in sediments from nearshore waters and inland lagoons varied across Vieques. In general, the inland lagoons had a significantly higher total PCB concentration ($p < 0.0001$) than non-inland lagoon areas. A nonparametric (Wilcoxon) analysis indicated no difference in the concentration of sediment total PCBs between strata (e.g., North 5 versus South 1) ($p = 0.4140$). There was no difference in the concentration of total PCBs in the north strata versus the south strata ($p = 0.2207$). Finally, if the north and south strata are combined (e.g., North 1 and South 1) to create five strata moving west to east (Figure 5.7), there were no significant differences in total PCBs ($p = 0.3158$) between these strata.

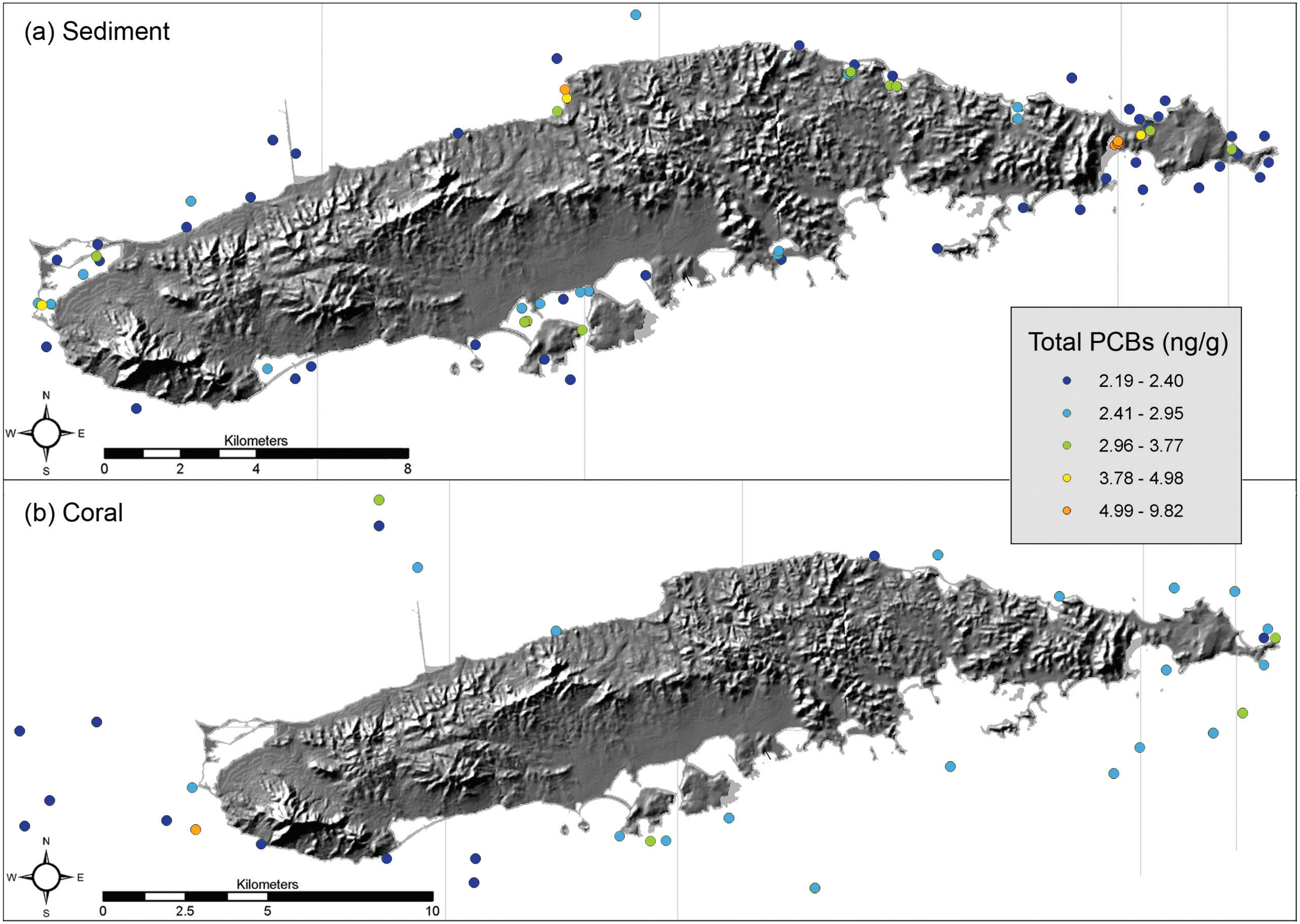


Figure 5.9. Total PCBs detected in the sediments (a) and in *Porites astreoides* (b).

Comparison Among Inland Lagoons. The sampling conducted in Vieques not only enabled comparisons between strata, but also comparisons in contaminant levels between nine inland lagoons (Figure 5.7) on the island. A Wilcoxon test indicated, however, there were no significant differences ($p = 0.1038$) between the nine lagoons for total PCBs in sediments.

Comparison with Sediment Quality Guidelines. Table 5.4 contains additional information on the levels of total PCBs detected in the sediments, along with sediment quality guidelines. The mean and median levels for total PCBs found in the sediments sampled in Vieques were well below all the guidelines shown in Table 5.4, as was the maximum total PCBs concentration (9.82 ng/g).

Table 5.4. Total PCBs in Vieques sediments and guidelines.

Vieques Results	Concentration (ng/g)
Vieques sediment total PCBs minimum	2.19
Vieques sediment total PCBs maximum	9.82
Vieques sediment total PCBs mean	2.86 ± 0.14
Vieques sediment total PCBs median	2.38
NOAA NS&T	
Mean	13.7 ± 2.70
Median	2.16
85th Percentile	23.7
Guidelines	
Threshold Effects Limit (TEL)	21.6
Effects Range - Low (ERL)	22.7
Effects Range - Median (ERM)	180
Probable Effects Level (PEL)	189
Apparent Effects Threshold (AET)	130

PCBs and TOC. Because the concentration of total PCBs was not normally distributed, nonparametric correlations (Spearman's) were run. There was no correlation between sediment PCBs and TOC in the samples taken in Vieques. One possibility for the lack of significant correlation could be the consistently low levels of PCBs seen in the sediments throughout the study area.

PCBs and Grain Size. A nonparametric analysis of % fines and total PCBs in the sediments, however, did reveal a significant ($p < 0.0001$) correlation. As noted, finer grain size sediments provide binding sites for contaminants including organics, however, it is not clear why there would be a correlation between total PCBs and % fines, but not for TOC.

Normalization of Total PCBs to TOC and Fines. The results of the normalization of total PCBs in the sediments to TOC (total PCBs/%TOC) and to % fines (total PCBs/% fines) for each site sampled is shown in Appendix I. As with the PAHs, because of the fairly low concentrations of total PCBs in the sediments seen throughout the study area, the normalizations were not revealing in terms of sources for the PCBs detected.

PCBs in Corals. The concentration of total PCBs found in the coral tissues are presented in Figure 5.9b. The mean concentration of total PCBs was 2.63 ± 0.11 ng/g; the median was 2.57 ng/g. The concentration of total PCBs in coral tissues was not significantly different from total PCBs found in the sediments ($p > 0.05$, Chi-Square = 0.3763). In southwest Puerto Rico, Pait et al. (in press) calculated a mean total PCBs concentration of 4.01 ± 1.03 ng/g in *P. astreoides* from southwest Puerto Rico, similar to what was found in *P. astreoides* in Vieques. A number of Wilcoxon tests were carried out to assess how the distribution of total PCBs in the coral tissues varied around Vieques. The results indicated there were no differences in the concentration of total PCBs in the north strata versus the south strata ($p = 0.4775$), nor were there differences in the concentration of coral total PCBs between strata (e.g., North 5 versus South 1) ($p = 0.8151$), or total PCBs in corals moving west to east ($p = 0.4049$) (Strata 1 to 5, Figure 5.7).

Normalization of Coral Tissues to Lipid Content. Appendix K contains the results of normalizing total PCBs in *P. astreoides* to lipid content. Because of the low concentrations of total PCBs seen throughout the study area, the normalization of total PCBs to lipid content was not very revealing.

PCB Accumulation in Corals. There are few articles on the accumulation of PCBs in corals. El Nemr et al. (2004) analyzed *Acropora sp*. tissues from a number of sites along the Egyptian Red Sea Coast. The average concentration of seven PCB congeners in the coral tissues was 18 ng/g (El Nemr et al. 2004), higher than was found in Vieques. Miao et al. (2000) analyzed coral (*Porites lobata*) samples for a number of PCB congeners from four sites in the French Frigate Shoals in the Pacific Ocean. Seventeen of the congeners analyzed by Miao et al. (2000) were also analyzed in the coral samples from Vieques. The approximate mean concentration for these congeners in *P. lobata* was 110 ng/g, substantially higher than the mean for total PCBs in *P. astreoides* from Vieques.

Comparison with Other Work in Vieques. NOAA and Ridolfi (2006) found 7.6 ng/g of total PCBs, representing nine Aroclors, in the tissues of the land crab *C. guanhumi* in Vieques, similar to the maximum total PCBs found in the sediments in the current study. The land crab where PCBs were detected was collected in Laguna Kiani. Comparison of data from different sources (i.e., crab tissue vs. coral tissue or sediments) can describe possible bioaccumulation (not obvious from the results present here) as well as contamination in a different matrix.

Total DDT

Thirty-one organochlorine pesticides and related compounds and degradation products were analyzed in the sediments and coral tissues collected in Vieques. The results for the individual organochlorine pesticides can be found in Appendix L and M. A more detailed discussion of the results for DDT, chlordane and endosulfan follow. These organochlorine pesticides were chosen as they had more of the detectable, and in the case of DDT, higher concentrations in the samples collected in Vieques.

DDT in Sediments. Figure 5.10a shows the distribution of total DDT in the sediments collected in Vieques. Total DDT is the sum of the parent isomers (4,4'-DDT and 2,4'-DDT) and degradation products DDE, DDD and DDMU. The mean concentration of total DDT in the sediments was 23.6 ±16.5 ng/g, higher than the NS&T mean (3.11 ng/g) (Table 5.5). The higher mean and large standard error of the mean for Vieques were due to elevated DDT levels in some of the inland lagoon sites. The NS&T Program median for total DDT is 0.40 ng/g, higher than the total DDT median (0.10 ng/g) found in the sediments in Vieques.

The highest concentration of total DDT found in the sediments from Vieques (1,274 ng/g) was from an inland lagoon site (46P) adjacent to Blue Beach, in the former Eastern Maneuver Area of the VNTR (Figure 5.1 and Figure 5.10a). The second highest total DDT concentration (178 ng/g) was also found in a sediment sample (21P) from the Eastern Maneuver Area, from a lagoon adjacent to Puerto Negro on the northeastern part of the island. The higher concentrations of total DDT were found in the inland lagoon areas, as can be seen in Figure 5.10a. This is perhaps not surprising as the use of DDT in the past likely occurred in the inland areas where mosquitoes and other pests were a problem. The application of DDT in this part of Vieques was more likely for non-agricultural uses as military training exercises were conducted in these areas. It should also be noted, however, that of the 78 sediment samples collected in Vieques for this project, approximately 70% contained less than 1 ppb total DDT; 22% of the sites contained no detectable DDT at all.

Summary for Total DDT

- *The highest total DDT concentration in the sediments was 1,274 ng/g and was found in Lagoon 10 adjacent to Blue Beach in the former Eastern Maneuver Area (EMA).*
- *Concentrations of total DDT were higher in the inland lagoon areas of the island.*
- *The stratum containing the EMA had significantly higher total DDT in the sediments than the other strata.*
- *The concentration of total DDTs in the sediments exceeded the Effects Range Median value of 46.1 ng/g at four locations in Vieques, indicating likely impacts (toxicity) in sediment-dwelling organisms in these areas.*
- *Overall, the concentration of total DDT in coral (Porites astreoides) was not significantly different from the concentration in the sediments.*

The results for total DDT in the sediments can be compared with work recently completed in southwest Puerto Rico (Pait et al. 2007). The mean total DDT concentration in the sediments from southwest Puerto Rico was 2.10 ± 1.26 ng/g, lower than the mean found in Vieques. Even if the value for total DDT from 46P is removed from the calculation, the mean total DDT for Vieques would be 7.38 ±2.81 ng/g.

Comparison Between Strata. As with the other contaminant classes, a series of statistical analyses were carried out to understand how the distribution of total DDT quantified in the sediments varied across the island of Vieques. Not surprisingly, a nonparametric Wilcoxon test indicated that the concentration of total DDT from the inland lagoons was significantly higher ($p < 0.0001$) than the nonlagoon areas. A nonparametric (Wilcoxon) analysis indicated a significant difference ($p = 0.0279$) in the concentration of sediment total DDT between strata (e.g., North 5 versus South 1), however, a comparison (Tukey HSD) of ranked values did not reveal any significant differences between individual strata. There were no differences ($p = 0.3767$) in the north strata versus the south strata. If the strata (e.g., North 1 and South 1) are combined to form five strata moving in a west

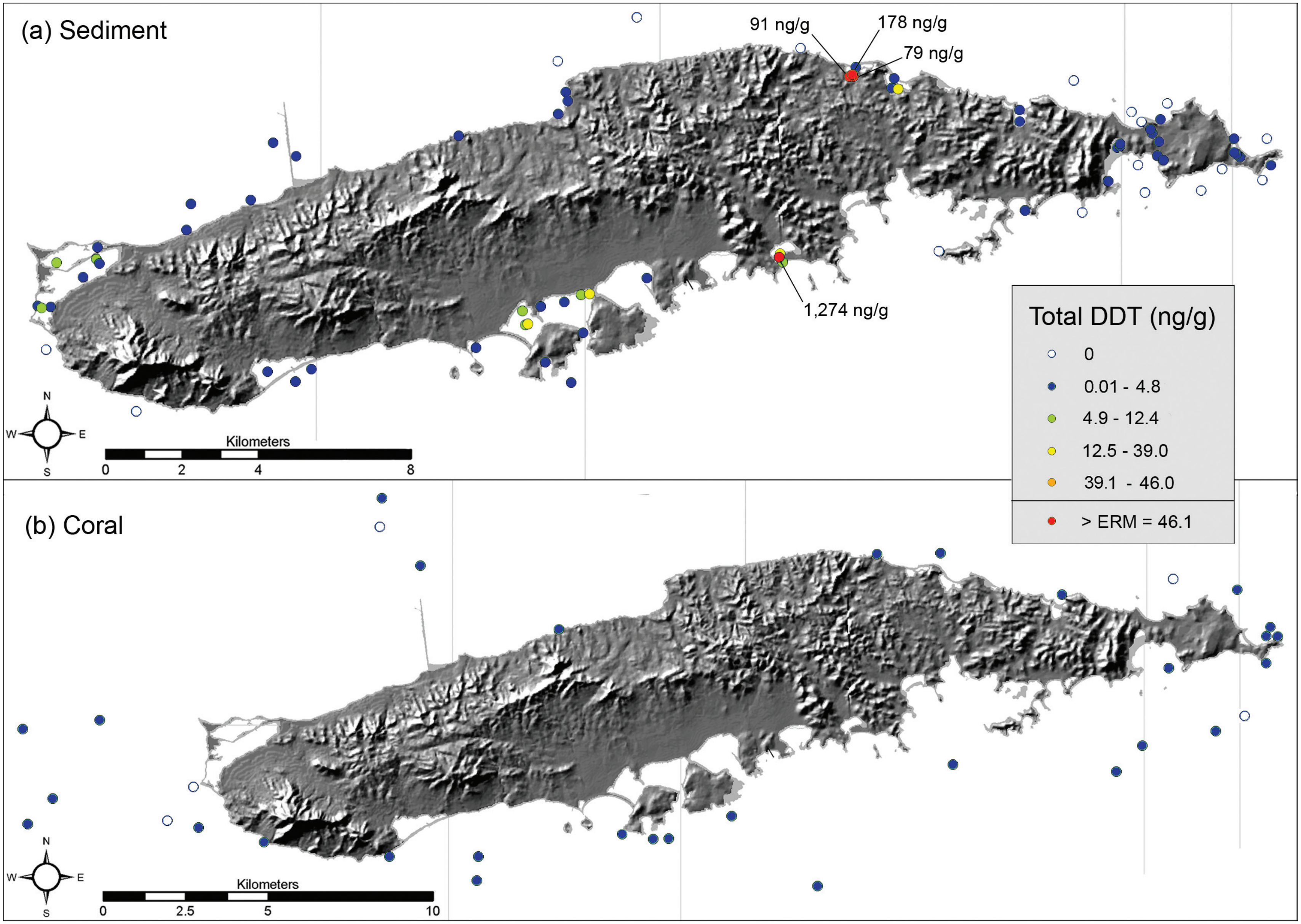


Figure 5.10. Total DDT detected in the sediments (a) and in *Porites astreoides* (b).

to east direction (Figure 5.7), Stratum 3 which contains the Eastern Maneuver Area where the higher concentrations of total DDT were found, was significantly different (p = 0.0082, Tukey HSD on the ranked data).

Comparison Among Inland Lagoons. The October 2007 sediment sampling in Vieques concentrated on a number of inland lagoons, and along with the results from the May 2007 sampling, enable a comparison of contaminant concentrations between nine inland lagoons (Figure 5.7) on the island. For total DDT, a Wilcoxon test indicated a significant difference (p = 0.0027) between the nine lagoons sampled. A pairwise comparison (Tukey HSD) of the ranked data indicated that total DDT in the sediments in Lagoon 4 (Laguna Algodones) on the north shore, Lagoon 5 near Blue Beach (which contains 46P) and Lagoon 3 near Ensenada Sombe had significantly different (higher) total DDT concentrations than Lagoons 6 through 9.

Comparison with Sediment Quality Guidelines. Table 5.5 contains additional information on the levels of total DDT detected in the sediments, along with a number of established sediment quality guidelines. Four sediment samples, including 46P, and all the samples taken from the lagoon adjacent to Puerto Negro (21P (178 ng/g), 22P (79 ng/g) and 23P (91 ng/g)) were not only above the ERL, but also above the ERM value of 46.1 ng/g, indicating that benthic organisms inhabiting these lagoons may be impacted by the concentration of DDT. These same sites also exceeded the PEL or probable effects level (51.7 ng/g). The Apparent Effects Threshold or AET, was developed by the State of Washington and represents the concentration above which significant biological effects (toxicity) in benthic infaunal organisms may be expected. The AET for total DDT is 11 ng/g, lower than the ERM. In Vieques, there were 10 sites above the AET for total DDT, including the four listed above; all were located in the inland lagoon areas.

Table 5.5. Total DDT in Vieques sediments and guidelines.

Vieques Results	Concentration (ng/g)
Vieques sediment total DDT minimum	0
Vieques sediment total DDT maximum	1,274
Vieques sediment total DDT mean	23.6 ± 16.5
Vieques sediment total DDT median	0.10
NOAA NS&T	
Mean	3.11 ± 0.896
Median	0.395
85th Percentile	3.49
Guidelines	
Threshold Effects Limit (TEL)	3.89
Effects Range - Low (ERL)	1.58
Effects Range - Median (ERM)	46.1
Probable Effects Level (PEL)	51.7
Apparent Effects Threshold (AET)	11

Parent and Degradation Products of DDT. Because the measurement of total DDT is made up of both the parent isomers and degradation products, the ratio of parent compounds to degradation products can provide some insight into the relative age or “freshness” of the DDT present. Total DDT concentrations containing higher ratios of the parent compound are more likely to be recently introduced into the environment. For sites 21P, 22P and 23P, the DDT degradation products accounted for approximately 97% of the total, indicating that the DDT present had degraded over time. At 46P, which had a total DDT concentration of 1,274 ng/g, approximately 68% of the total DDT present consisted of the parent compounds, which could indicate more recent introduction of the pesticide into the environment. The source of the DDT at this site is currently unknown, however, the high concentration along with the higher levels of the parent compounds could indicate a more recent spill or dumping of DDT at or near the site sampled. According to the U.S. Navy, the area around Blue Beach once served as a fuel offloading site (Hood, personal communication). It is possible that containers of DDT may have been spilled at this site, or perhaps DDT was over applied to control insect pests in the area.

DDT and TOC. Because the concentration of total DDT was not normally distributed, nonparametric correlations (Spearman’s) were run. There was a significant (p < 0.0001) positive correlation between sediment total DDT and TOC in the samples taken in Vieques. As noted, organics typically bind to sediment TOC, and the areas with elevated levels of total DDT (inland lagoons) were associated with sediments containing higher levels of TOC.

DDT and Grain Size. A nonparametric analysis of % fines and total DDT in the sediments, also revealed a significant (p < 0.0001) correlation. Finer grain size sediments provide binding sites for contaminants including DDT.

Normalization of Total DDT to TOC and Fines. The results of the normalization of total DDT found in the sediment to TOC (total DDT/%TOC) and to % fines (total DDT/% fines) for each site sampled is shown in Figure

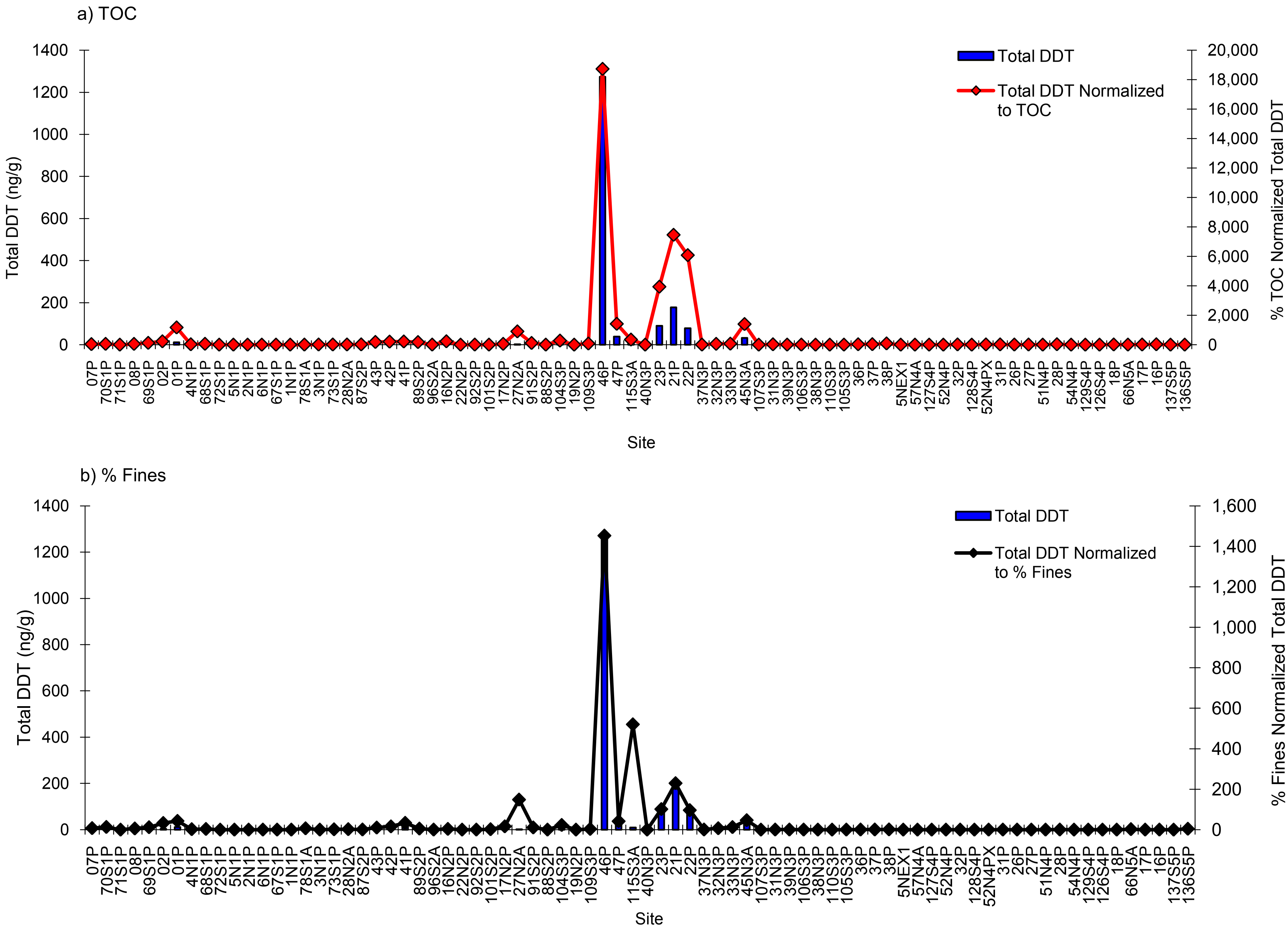


Figure 5.11. Total DDT in sediments normalized to TOC (a) and % fines (b).

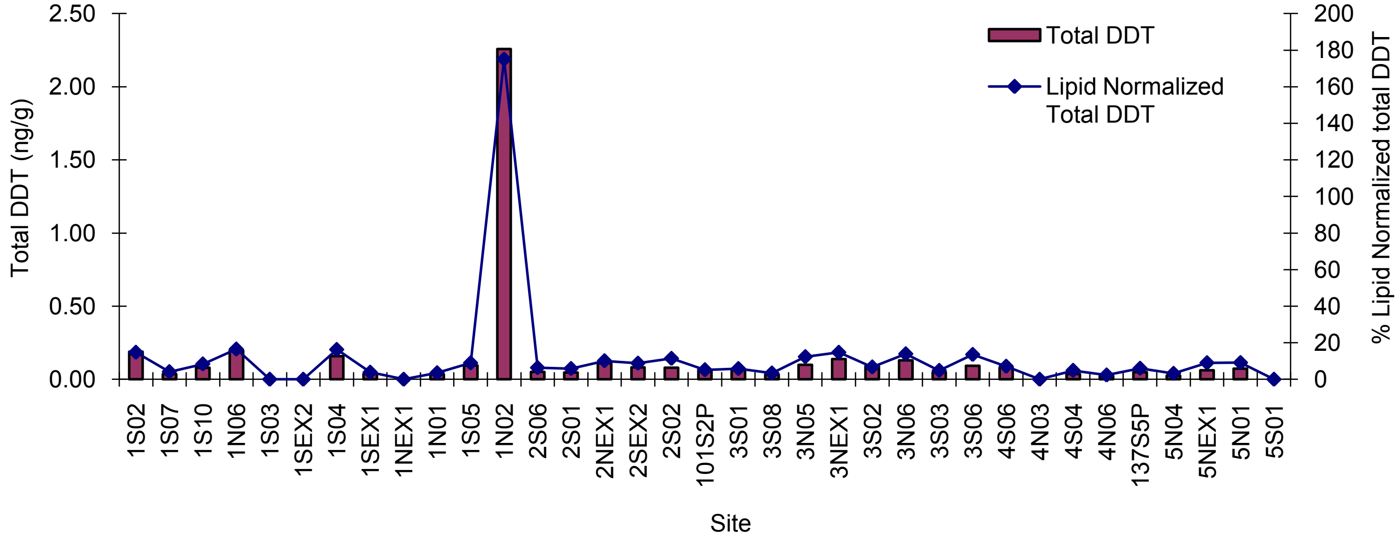


Figure 5.12. Total DDT in *P. astreoides* tissues normalized to lipid content.

5.11. The concentrations of total DDT in the sediments are plotted on both graphs in addition to the normalized values, and the sites are oriented in a west to east direction to make them comparable to the information presented in Figure 5.10. Normalizations of this type are sometimes useful for identifying sources of contaminants (Birch 2003; Burgess et al. 2001). Figure 5.11 also provides a second opportunity to compare total DDT detected in the sediments between sites. As can be seen from the blue bars in Figure 5.11, the higher concentrations of total DDT found in the inland lagoons at 46P along with 21P, 22P, and 23P are apparent. It can be also be seen from this graphic and from Appendix L, that a large number of sediments sampled in Vieques had a total DDT concentration of 1 ng/g or less.

In Figure 5.11a, total DDT normalized to TOC is displayed by the red line in the graph. There was a large spike in the TOC-normalized total DDT concentration at 46P near Blue Beach, indicating this area is a likely source for the DDT in this area. A higher total DDT normalized concentration was also visible at 21P, 22P, and 23P on the north side of Vieques in the Eastern Maneuver Area near Puerto Negro. In Figure 5.11b a similar pattern was found when total DDT concentration was normalized to % fines (i.e., higher normalized concentrations at 46P and at 21P, 22P, and 23P). A smaller spike was also apparent at 115S3A which had a lower (1.71%) concentration of fines and a total DDT concentration of 8.92 ng/g (Appendix L).

DDT in Corals. The concentration of total DDT found in the coral tissues are presented in Figure 5.10b. The mean concentration was 0.13 ± 0.07 ng/g; the median was 0.06 ng/g. A Wilcoxon test indicated that the concentration of total DDT in the coral tissues, however, was not significantly different from total DDT found in the sediments ($p = 0.1397$). In southwest Puerto Rico, Pait et al. (in press) calculated a mean total DDT concentration of 0.09 ± 0.08 ng/g in *P. astreoides*, similar to what was found in *P. astreoides* in Vieques.

A number of Wilcoxon tests were carried out to assess how the distribution of total DDT in the coral tissues varied across Vieques. The results indicate there were no differences in the concentration of total DDT in the corals in the north strata waters versus the south strata ($p = 0.5229$), nor were there differences in the concentration of coral total DDT between strata (e.g., North 5 versus South 1) ($p = 0.3306$), or total DDT in corals moving west to east ($p = 0.2634$) (Strata 1 to 5, Figure 5.7).

<u>Normalization of Coral Tissues to Lipid Content</u>. Figure 5.12 shows the results of normalizing total DDT in *P. astreoides* to lipid content. From Figure 5.12, it can be seen that the normalized concentration of total DDT closely followed the pattern of actual concentrations. There was one larger normalized total DDT peak. The coral sample with the higher normalized total DDT concentration (1N02), however, was on the northern side of Vieques, near Mosquito Pier. The sediment sample with the higher total DDT was located on the south side of the island, near Blue Beach.

<u>DDT Accumulation in Corals</u>. A few studies were found that quantified DDT and its metabolites in coral tissues. Glynn et al. (1995) collected and analyzed sediment and *P. astreoides* for residues of total DDT from the Florida Keys National Marine Sanctuary, in the area near Key Largo. The highest concentration detected was 0.01 ng/g. Glynn et al. (1989) also looked at total DDT in *P. astreoides* further north, in Biscayne National

Park, in an area known as Alina's Reef, and detected higher concentrations, ranging from 3.41 - 43.56 ng/g. In the current study, the highest total DDT concentration in *P. astreoides* was 2.26 ng/g. El Nemr et al. (2004) detected a mean total DDT concentration of 5.7 ± 0.8 ng/g (dry weight) in coral tissues from the Egyptian Red Sea Coast.

Comparison with Other Work in Vieques. NOAA and Ridolfi (2006) and ATSDR (2006) found concentrations of total DDT in Vieques, ranging from 0.47 – 283.8 ng/g. Detections were in the tissues of the land crab *C. guanhumi* and in the fiddler crab *(Uca sp)*. The highest DDT detections from these studies in increasing order were land crab from Red Beach (187.2 ng/g), land crab from Laguna Kiani (203.2 ng/g) and fiddler crab from Red Beach (283.8 ng/g). The highest total DDT concentration at Blue Beach from either of these studies was 103.3 ng/g in the fiddler crab. The concentration of total DDT in the sediments from the inland lagoon adjacent to Blue Beach (1,274 ng/g) from the current study appears to be the highest DDT level detected in any matrix in Vieques to date. Comparison of data from different sources (i.e., crab tissue vs. coral tissue or sediments) can describe bioaccumulation as well as contamination patterns in different matrices.

Other Pesticides

A number of other chlorinated pesticides were detected in the sediments and coral tissues in Vieques (Appendix L and M), including total chlordane (alpha-chlordane, gamma-chlordane, heptachlor, heptachlorepoxide, oxychlordane, trans-nonachlor, and cis-nonachlor) total endosulfan (endosulfan I and II and endosulfan sulfate), dieldrin, aldrin, endrin, gamma-HCH (lindane), and chlorpyrifos. All of these compounds, however, were at concentrations of less than 1 ng/g in both sediments and tissues. Maps of total chlordane and total endosulfan in sediments are shown in Figures 5.13 and 5.14, respectively.

Many currently used agricultural pesticides are not included in the NS&T list of core analytes, as they are water soluble and therefore less likely to accumulate in sediments and coral tissues, to the level where they could be detected. However, there appears to be little agriculture on Vieques, and so it would be unlikely that a water soluble herbicide such as atrazine would have been detected in the samples collected for this project.

Chlordane was used in the past as an insecticide. A primary non-agricultural use of chlordane was the treatment of wooden structures to prevent damage by termites. The mean total chlordane concentration in the sediments was 0.04 ±0.01 ng/g. The ERL for chlordane is 0.5 ng/g; the TEL is 2.26 ng/g. The highest total chlordane detected in the sediments in Vieques (0.67 ng/g) was at 28P (Figure 5.13) in the Live Impact Area, and was slightly above the ERL. In *P. astreoides*, the mean total chlordane was 0.12 ±0.03 ng/g. In Southwest Puerto Rico (Pait et al. 2007), the mean total chlordane concentration in the sediments was 0.15 ±0.06 ng/g.

Total endosulfan in the sediments is shown in Figure 5.14. The mean total endosulfan concentration in the sediments from Vieques was 0.02 ±0.01 ng/g. The highest concentration of total endosulfan in the sediments was 0.36 ng/g. No ERL, TEL or AET exist for this pesticide. Only one coral sample (1N01) had a detectable

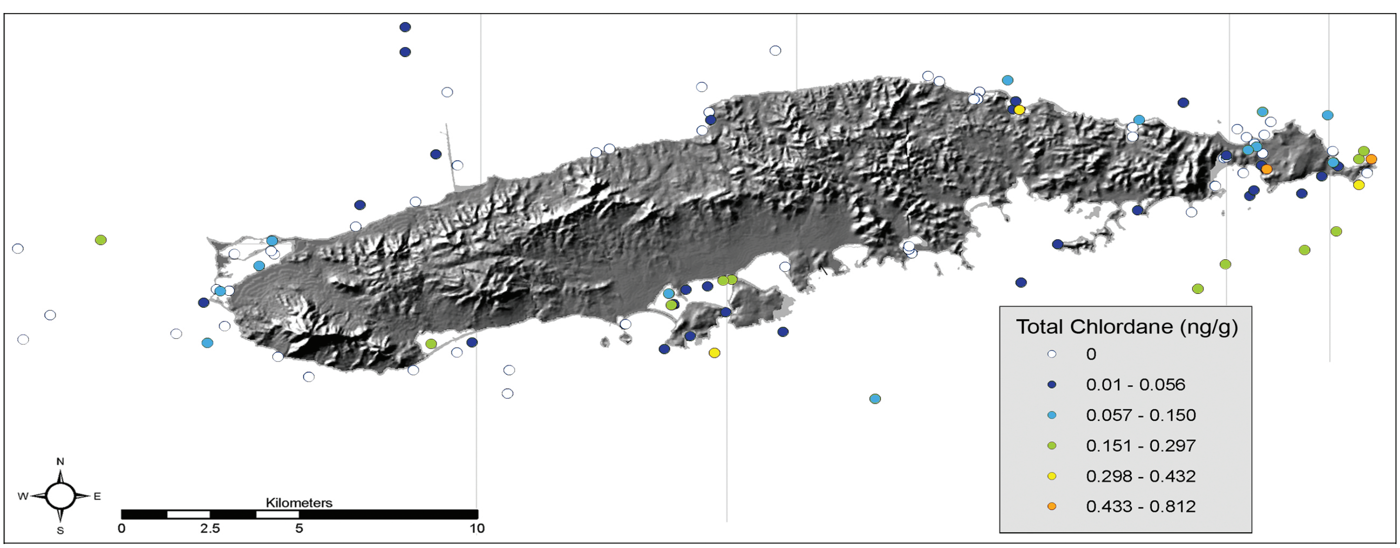


Figure 5.13. Total chlordane detected in the sediments.

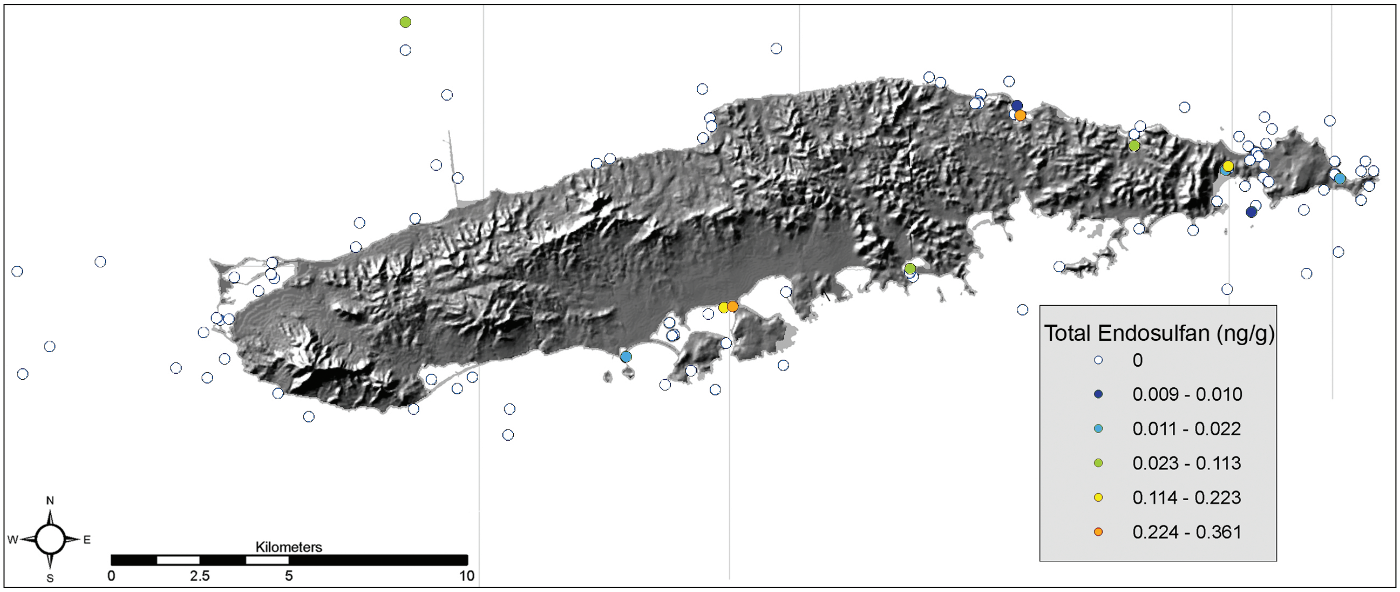


Figure 5.14. Total endosulfan detected in the sediments.

level of total endosulfan (0.09 ng/g). In southwest Puerto Rico, the mean concentration of total endosulfan in *P. astreoides* was 0.18 ±0.06 ng/g (Pait et al. 2007).

Energetics

For this project, a total of 15 energetics (explosives) and related compounds were analyzed in the sediment samples, and are shown in Table 5.1. The assessment of energetics in the sediment samples collected from Vieques was carried out because of their use as part of the naval training activities that occurred on parts of Vieques over the years. Perchlorate, used in solid rocket fuels was analyzed in selected sediment samples. The compounds 2,4,6-trinitrotoluene (TNT), HMX (High Melting Explosive), RDX (Royal Demolition Explosive) and Tetryl (2,4,6-trinitrophenyl-n-methylnitramine) are the parent energetics. Thermal degradation products include 1,3,5-trinitrobenzene, 2,4-dinitrotoluene, and 2,6-dinitrotoluene. The other energetic-related compounds listed in Table 5.1 are either impurities or microbial degradation products (Becker 1995). The analysis of energetics represents an expansion of the chemicals analyzed within NOAA's NS&T Program.

The results of the analysis for energetics is shown in Appendix N. For this project, the 78 sediment samples were initially analyzed using EPA Method 8330. From that analysis, 14 sites showed possible detections. To confirm the presence of the energetics, the 14 sediment samples were reanalyzed using Method 8330 followed by liquid chromatography/mass spectrometry/mass spectrometry (LC/MS/MS). The sites included in the reanalysis are indicated in Appendix N. Samples remained frozen at -20°C prior to reanalysis. The LC/MS/MS analysis was used to confirm the identity and concentration of any energetics. The results of the reanalysis indicated that the energetic compounds were either not found in the sediment samples analyzed, or because of matrix interferences coupled with very low concentrations, could not be quantified. Interpretation of the results of the analyses provided by TDI-Brooks International is also included in Appendix N.

Summary for Energetics

- *A total of 78 sediment samples were analyzed for 15 energetics (explosives) and related compounds.*
- *From the original analysis, there were 14 samples with possible detections of energetics.*
- *These samples were reanalyzed using liquid chromatography/mass spectrometry (LC/MS/MS) in an effort to confirm the presence of any energetics.*
- *The results of the reanalysis indicated that the energetic compounds were either not present in these samples, or because of matrix interferences coupled with very low concentrations, could not be quantified.*

The results from this study can be compared with those from other areas. In New Jersey, a study was conducted in the former Raritan Arsenal to determine whether contaminated soils and sediments within the former arsenal posed an ecological risk (USACOE 2008). As part of the baseline ecological risk assessment, estuarine sediment samples were analyzed for a number of energetics. None of the estuarine sediment samples analyzed contained energetics above the reporting limit. In Bremerton, WA, an ecological risk assessment Tier 1 screening was carried out in an area known as the Jackson Park Housing Complex (JPHC). Historically, the area had served as the U.S. Naval Ammunition Depot (NAD), Puget Sound. Activities included storage, production, demilitarization and burning of ordnance. The facility was decommissioned in 1959 (NAVFAC, 2007), and subsequently the site was converted to a residential complex for military personnel. As part of remedial actions at the site, sediments were collected in Ostrich Bay, and analyzed for a variety of contaminants including energetics. Maximum concentrations of the energetics detected included: 2,6-dinitrotoluene (0.68 μg/g), RDX (0.29 μg/g), Tetryl (0.03 μg/g), and nitrobenzene (0.008 μg/g). Decarlo et al. (2007) collected and analyzed 96 sediment and 46 fish samples in an area off Oahu, Hawaii known locally as Ordnance Reef, as part of a project to assess the extent of discarded military munitions and the presence of munitions constituents (energetics and metals). Decarlo et al. (2007) did not detect RDX, TNT or Tetryl, however, dinitrotoluene was detected at four sediment samples; no energetics or related compounds were detected in the fish sampled as part of that project.

Image 5.4. Semi-dry lagoon in the LIA, with bomb craters in the background, and ordnance in the foreground.

Comparison with Other Work in Vieques. A number of other documents have been published on the analysis of energetics in Vieques. CH2MHILL (2007) detected no energetics in 79 soil samples collected in the VNTR. NOAA and Ridolfi (2006) detected no energetics in crab tissue samples in 12 locations across Vieques. ATSDR (2006) found 0.97 μg/g of HMX in fiddler crab (*Uca sp.*) tissues taken in the former LIA. Barton and Porter (2004), however, detected TNT in sediment samples as high as 4,380 μg/g adjacent to an unexploded 2,000 pound bomb on the ocean floor, and in a brain coral (*Diploria labyrinthiformis*) tissue sample (252 μg/g) adjacent to the *USS Killen* stern.

Butyltins

The results of the analyses of butyltins is shown in Appendix O and P. As noted, tributyltin or TBT was used in the past as an antifouling agent, primarily on boat hulls. The degradation of tributyltin results in di- and then monobutyltin, which are also included in the appendices. Tetrabutyltin is an impurity produced in the manufacture of TBT.

Summary for Tributyltin (TBT)

- *There were 10 detections of TBT in the sediments in Vieques.*
- *The highest concentration of TBT was 1.23 ng/g and was found in Punta Arenas in the northwest portion of Vieques.*
- *There were no differences in the concentration of TBT in the sediments between inland lagoon and non-inland lagoon areas..*
- *There were no differences in TBT concentrations in sediments between any of the strata.*
- *The concentration of TBT in coral (Porites astreoides) was not significantly different from the concentration in the sediments.*

TBT in Sediments. There were 10 detections of TBT in the sediments sampled in Vieques (Figure 5.15a and Appendix O). The highest detection of TBT was 1.23 ng/g at 89S2P, located in Bahia Mosquito. The mean concentration of TBT in Vieques sediments was 0.04 ± 0.02 ng/g. The mean for TBT from NOAA's NS&T Program is 1.43 ng/g. The Vieques mean for dibutyltin was 0.30 ± 0.03 ng/g and for monobutyltin 0.41 ± 0.09 ng/g. Monobutyltin had the highest concentration of any of the butyltins found in Vieques, however dibutyltin was found more frequently. Eight sediment samples exceeded the NS&T 85th

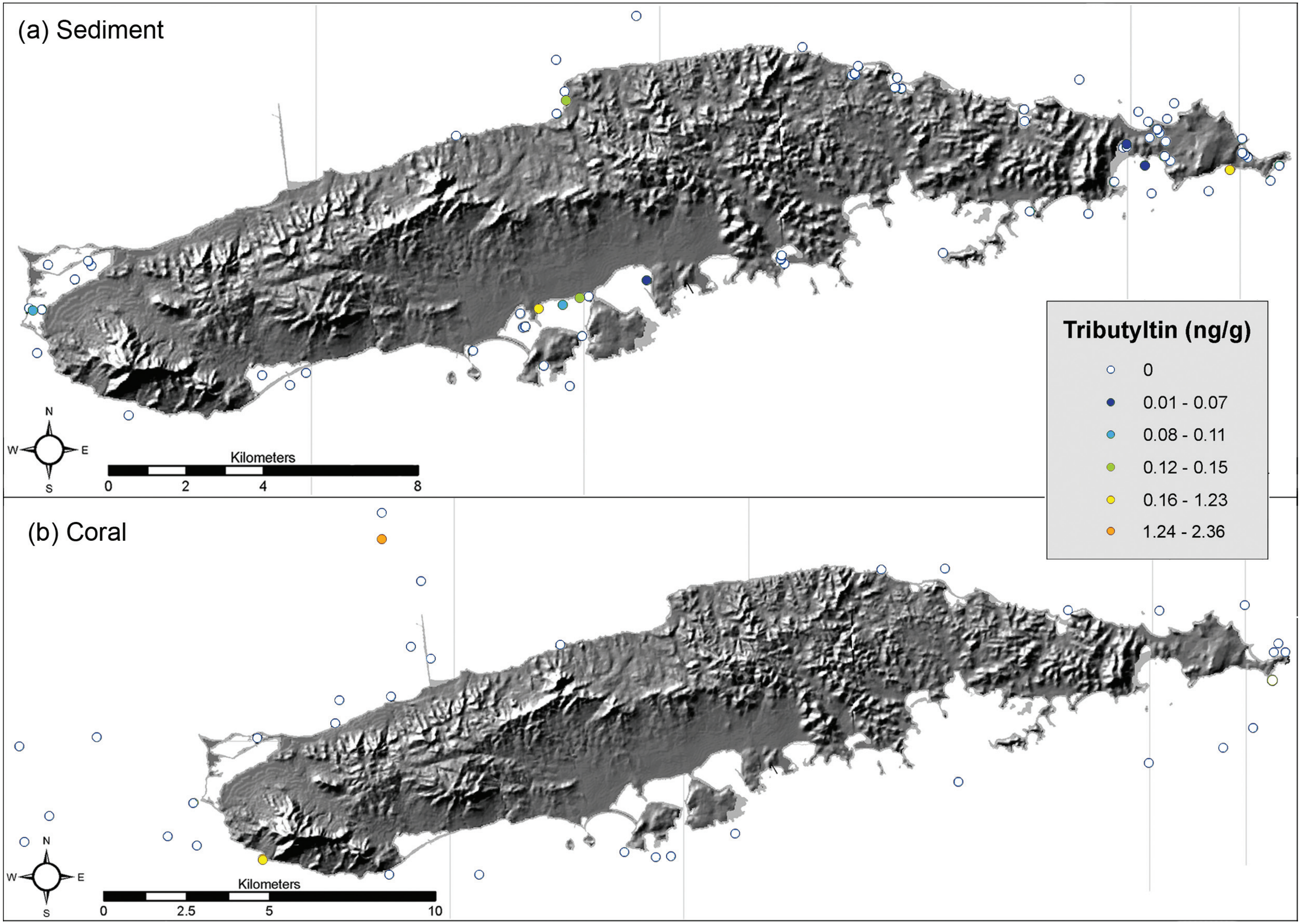


Figure 5.15. Tributyltin in sediments (a) and in *Porites astreoides* (b).

percentile for monobutyltin (1.28 ng/g). Tetrabutyltin was detected once in the sediments of Bahia Mosquito (0.22 ng/g) above the NS&T 85th percentile of 0.16 ng/g. The results for TBT found in the sediments in Vieques can be compared with work recently completed in southwest Puerto Rico (Pait et al. 2007). The mean concentration of TBT in the sediments in southwest Puerto Rico was 0.01 ± 0.01 ng/g, lower than the mean TBT concentration found in Vieques.

Comparisons Between Strata. A series of statistical analyses were carried out to assess how the distribution of TBT in the sediments varied across Vieques. In contrast to most of the other contaminants discussed, there were no significant differences between inland lagoon and non-inland lagoon areas ($p = 0.2954$). A nonparametric (Wilcoxon) analysis indicated no difference in the concentration of sediment TBT between strata ($p = 0.5474$). There was no difference in the concentration of TBT in the north strata versus the south strata on Vieques ($p = 0.1769$). Finally, if the north and south strata are combined (e.g., North 1 and South 1) to create five strata moving west to east, there were no significant differences in TBT ($p = 0.2498$) between the strata.

Comparison with Sediment Quality Guidelines. No sediment quality guidelines were located for TBT or its metabolites.

TBT in Corals. The mean concentration of TBT in *P. astreoides* (Figure 5.15b) was 0.08 ± 0.07 ng/g. The concentration of TBT in the coral tissues was not significantly different ($p = 0.3221$) from the concentration in the sediments. An analysis of variance using Wilcoxon's nonparametric test showed a significant difference between mono- and dibutyltin concentrations in coral tissues and sediments, with coral tissues having higher concentrations of both at the 95% confidence level. In the coral samples, monobutyltin was the dominant butyltin found, and is likely the result of TBT debutylization. Additional information on the butyltins detected in *P. astreoides* can be found in Appendix P.

Effects of TBT on Corals. Negri et al. (2002) investigated the effects of TBT in sediments on the coral *Acropora microphthalma*. Sediments were collected from an area where a cargo ship had grounded on the Great Barrier Reef in Australia. The grounding of the ship and subsequent wave action resulted in TBT sediment concentrations of 160 µg/g, copper concentrations of 1,180 µg/g, and zinc concentrations of 1,570 µg/g. Negri et al. (2002) diluted the sediments taken at the site of the grounding with sediments from a control site. Sediments diluted to 5 percent of the original concentration prevented successful settlement of coral larvae in the laboratory on preconditioned terracotta tiles. The tiles were preconditioned by placing them on control reefs for three months. Negri and Heyward (2001) investigated the effects of tributyltin on fertilization and larval settling of *A. millepora*. Gametes were collected from reefs in Western Australia, and brought back to the laboratory. The effective concentration of TBT which caused 50 percent inhibition (EC50) of fertilization after four hours was 200 µg/L. A second set of experiments was carried out to assess the effects of TBT on settlement and metamorphosis of larval *A. millepora*. The calculated concentration needed to inhibit 50 percent larval metamorphosis was only 2 µg/L.

Trace and Major Elements

A total of 16 trace and major elements were analyzed in the sediments; 14 elements were analyzed in coral tissues. An assessment of trace and major elements in the sediments and coral tissues collected in Vieques is of interest in part due to the previous military activities, which could be reflected in elevated concentrations of these elements in the samples collected.

A summary of the means and standard errors for the elements in sediments and coral tissues is shown in Table 5.6. Except for cadmium, the concentration of trace and major elements were lower, in some cases orders of magnitude lower, in the coral tissues. The highest mean concentration of any trace or major element analyzed in the sediments was aluminum at over 35,500 µg/g, or 35.5 parts per thousand. Silicon (18,240 µg/g) and iron (17,610 µg/g) had the second and third highest concen-

Table 5.6. Trace and major elements in sediments and coral tissues (*P. astreoides*).

Element	Sediment Mean (µg/g) ±SE	Coral Mean (µg/g) ±SE
Aluminum	35,530 ±3,530	30.75 ±4.33
Antimony	0.225 ±0.032	NA
Arsenic	4.37 ±0.33	0.241 ±0.137
Cadmium	0.133 ±0.031	0.194 ±0.018
Chromium	22.5 ±2.98	0.183 ±0.060
Copper	25.9 ±3.15	0.757 ±0.264
Iron	17,610 ±1920	51.2 ±15.0
Lead	5.42 ±0.55	0.074 ±0.001
Manganese	301 ±31.8	2.66 ±0.32
Mercury	0.019 ±0.003	<0.001
Nickel	7.80 ±1.07	0.896 ±0.290
Selenium	0.261 ±0.035	0.096 ±0.017
Silicon	18,240 ±10,750	NA
Silver	0.103 ±0.01	0.013 ±0.001
Tin	0.660 ±0.222	0.246 ± 0.012
Zinc	34.3 ±3.91	3.43 ±0.49

NA, not analyzed

trations in the sediments, respectively. Aluminum, iron, and silicon are major elements in the Earth's crust, so it is not surprising that there were higher concentrations of these elements relative to the others analyzed. Both trace and major elements are found naturally in the Earth's crust, however, the use and disposal of products containing these elements can result in elevated environmental concentrations, particularly for trace elements. In the coral tissues, the highest elemental concentration found was iron at 51 µg/g, followed by aluminum (31 µg/g) and zinc (3 µg/g).

A discussion of four elements, cadmium, chromium, copper, and lead in sediments and coral tissues follows. Brief summaries for sediments are subsequently provided for aluminum, arsenic, iron, manganese, mercury, nickel and zinc. These elements were chosen based on the pattens observed in the samples collected, likely use patterns, and reported toxicity for a number of the elements (e.g., cadmium, chromium and mercury). Detailed data for all the trace and major elements analyzed for this project can be found in Appendix Q and R.

Cadmium. The concentration of cadmium in the sediments and tissues of *P. astreoides* collected in Vieques is shown in Figure 5.16a and b, respectively. The scale on both maps is the same in order to make comparisons of cadmium between sediments and corals easier.

Cadmium in Sediments. The mean concentration of cadmium found in the sediments in Vieques was 0.13 ±0.03 µg/g. Roughly 60 percent of the sediment samples in Vieques contained no detectable cadmium. The mean concentration of cadmium found in the sediments in Vieques can be compared with what has been found nationwide in NOAA's NS&T Program. The mean concentration of cadmium in sediments sampled as part of the NS&T Program for 2006 and 2007 was 0.23 µg/g, somewhat higher than that found in Vieques.

The highest concentration of cadmium found in the sediment samples was 1.92 µg/g (Table 5.7) at 28P, an inland lagoon site located on the eastern end of Vieques near Bahia Salina del Sur, in the former LIA. The second highest sediment cadmium concentration (0.813 µg/g) was in the same inland lagoon, at 27P (Figure 5.1). The top five (28P, 27P, 26P, 36P, 31P) detections of cadmium were all inland lagoon sites in or adjacent to the LIA (Figure 5.16a). Seven sediment samples (28P, 27P, 26P, 36P, 31P, 32P, and 23P) collected from Vieques exceeded the NS&T 85th percentile (0.44 µg/g) for cadmium. In southwest Puerto Rico, Pait et al. (2007) detected a mean sediment cadmium concentration of approximately 0.01 µg/g, lower than that found in Vieques. Cadmium is used in a number of applications, including nickel-cadmium (Ni-Cd) batteries. Cadmium pigments are also used in paints and in corrosion control treatments for steel and aluminum products, including those used by the military (Ellor and Stemniski 2007). The somewhat elevated concentrations of cadmium in the LIA could be related to the military activities that have occurred there in the past.

Summary for Cadmium

- *The highest cadmium concentration in the sediments was 1.92 µg/g in Lagoon 8, inland of Bahia Salina del Sur in the former Live Impact Area (LIA).*
- *Concentrations of cadmium were higher in the inland lagoon areas of the island.*
- *The stratum containing the LIA had significantly higher cadmium in the sediments than one of the more western strata.*
- *The concentration of cadmium in the sediments exceeded the threshold Effects Range Low (ERL) and Threshold Effects Level (TEL) values at three sites in Lagoon 8 in the former LIA.*
- *Values around the threshold levels indicate the concentrations at which adverse effects may begin among sensitive life stages or species.*
- *The concentration of cadmium in coral (Porites astreoides) was significantly higher than in sediments.*

Comparison Between Strata. A series of statistical tests were carried out to see how the concentration of cadmium varied across Vieques, and how the concentration of cadmium varied with sediment grain size. Nonparametric (e.g., Wilcoxon), and then parametric analysis of the ranked values were used in the analysis. The concentration of cadmium was significantly higher in the inland lagoon areas ($p < 0.0001$). This may not be too surprising as cadmium and other trace and major elements tend to accumulate in sediments with smaller (e.g., clay) grain sizes (Manahan 1993). From Appendix C, it can be seen that most of the sediments from the inland lagoon areas contain higher levels of fines (% clay + % silt). A Wilcoxon nonparametric analysis indicated, however, that cadmium in the sediments did not vary ($p = 0.0517$) by stratum (e.g., North 5 versus South 1). A Wilcoxon test run to assess differences in the concentration of cadmium in the north versus the south strata, also indicated no significant difference ($p = 0.0849$). If the north and south strata are combined (e.g., North 1 and South 1) to create five strata moving west to east (Figure 5.7), there was a significant difference in the concentration of cadmium ($p = 0.0278$) between the strata. A pairwise comparison (Tukey HSD) of the ranked

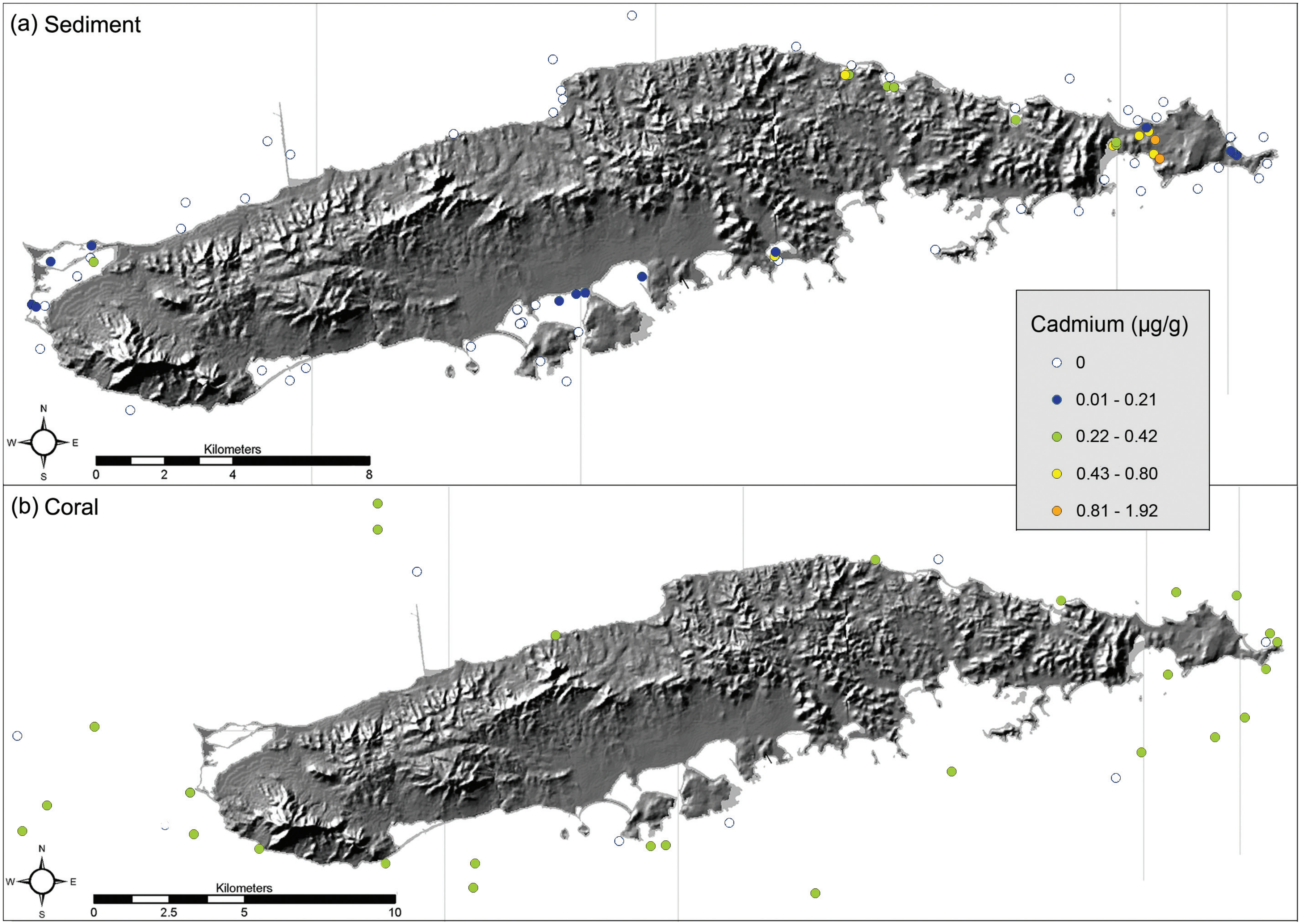


Figure 5.16. Cadmium in sediments (a) and in *Porites astreoides* (b).

values indicated that Stratum 4 (LIA) had significantly higher cadmium concentrations in the sediments than Stratum 2. A nonparametric analysis also indicated that cadmium in the sediment was correlated with the % fines ($p < 0.0001$).

Comparison Among Inland Lagoons. A Wilcoxon test indicated there were significant ($p = 0.0088$) differences in the concentration of cadmium between the nine inland lagoons included in the analysis. An analysis of the ranked data indicated that Lagoon 8 (Laguna Anones) was higher than a number of the other lagoons, particularly those on the west side of Vieques.

Table 5.7. Cadmium (Cd) in Vieques sediments and guidelines.

Vieques Results	Concentration (µg/g)
Vieques sediment Cd minimum	0
Vieques sediment Cd maximum	1.92
Vieques sediment Cd mean	0.15 ± 0.023
Vieques sediment Cd median	0
NOAA NS&T	
Mean	0.13 ± 0.03
Median	0.19
85th Percentile	0.44
Guidelines	
Threshold Effects Limit (TEL)	0.68
Effects Range - Low (ERL)	1.2
Effects Range - Median (ERM)	9.6
Probable Effects Level (PEL)	4.21
Apparent Effects Threshold (AET)	3

Comparison with Sediment Quality Guidelines. Some of the sediment quality guidelines established for cadmium are shown in Table 5.7. The concentration of cadmium at sites 28P, 27P, and 26P exceeded the Threshold Effects Limit or TEL, and 28P also exceeded the Effects Range-Low or ERL. Both the TEL and ERL represent threshold effects concentrations, meaning that concentrations below these values are unlikely to have biological impacts on sediment-inhabiting biota. Values between the ERL and ERM, could indicate that more sensitive species or life stages are beginning to experience some degree of toxic effects. No sediment concentrations, however, were above the PEL or ERM concentrations which would have indicated that effects were likely in sediment-inhabiting organisms.

<u>Cadmium in Corals</u>. The concentration of cadmium detected in the corals is shown in Figure 5.16b. The mean concentration was 0.19 ±0.02 µg/g. The mean concentration in *P. astreoides* was higher than in the sediments (0.15 µg/g), and a Wilcoxon test indicated that this difference was significant ($p = 0.0003$). This was the only trace element found to be higher in coral tissues than in sediments.

Effects of Cadmium on Corals. Cadmium in the aqueous phase has been shown to impact corals, but typically at higher concentrations. Reichelt-Brushett and Harrison (1999) looked at fertilization success in the brain coral *Goniastrea aspera* at concentrations up to 200 µg/L, and in the scroll coral *Oxypora lacera* up to 1,000 µg/L and found no effects. Reichelt-Brushett and Harrison (2005) did find a significant effect in finger coral (*Acropora tenuis*), but at concentrations at or above 5,000 µg/L.

<u>Comparison with Other Work in Vieques</u>. Cadmium has been documented in Vieques by numerous studies (ATSDR 2006; Barton and Porter 2004; Massol-Deya et al. 2005; NOAA and Ridolfi 2006; CH2MHILL 2007). The highest level of cadmium found in the sediments in the current study was below the UTL calculated by CH2MHILL (2007). Cadmium detected by NOAA and Ridolfi (2006) in land crab tissues (*C. guanhumi*) across the island ranged from 0.01 – 0.52 µg/g. CH2MHILL (2002) found no cadmium in the sediments of Laguna Kiani or Laguna Playa Grande. The highest concentration of cadmium observed by Barton and Porter (2004) was in brain coral tissues (*Diploria labyrinthiformis*) (46.8 µg/g) and was adjacent to underwater unexploded ordnance.

Chromium. The concentration of chromium detected in the sediments and in *P. astreoides* from Vieques is shown in Figure 5.17a and b, respectively. The scale is the same on both maps in order to make comparisons between sediments and coral tissues easier.

<u>Chromium in Sediments</u>. The mean concentration of chromium found in the sediments in Vieques was 22.5 ±2.98 µg/g. The NS&T mean for chromium in sediments is 79.7 ±5.33 µg/g (Table 5.8) for the collection year 2006 and 2007, higher than the mean found in the sediments from Vieques. The highest concentration of chromium found in the sediments sampled in Vieques was 178 µg/g at 52N4PX (Figure 5.1), an inland lagoon site (Lagoon 7) located in the eastern end of Vieques near Bahia Icacos on the northern shore, and in the former LIA. The second highest sediment concentration was found in another inland lagoon, at 38P adjacent to the LIA, at a concentration of 85.2 µg/g. Four of the top five (52N4PX, 38P, 36P, 31P, 37P) detections of chromium

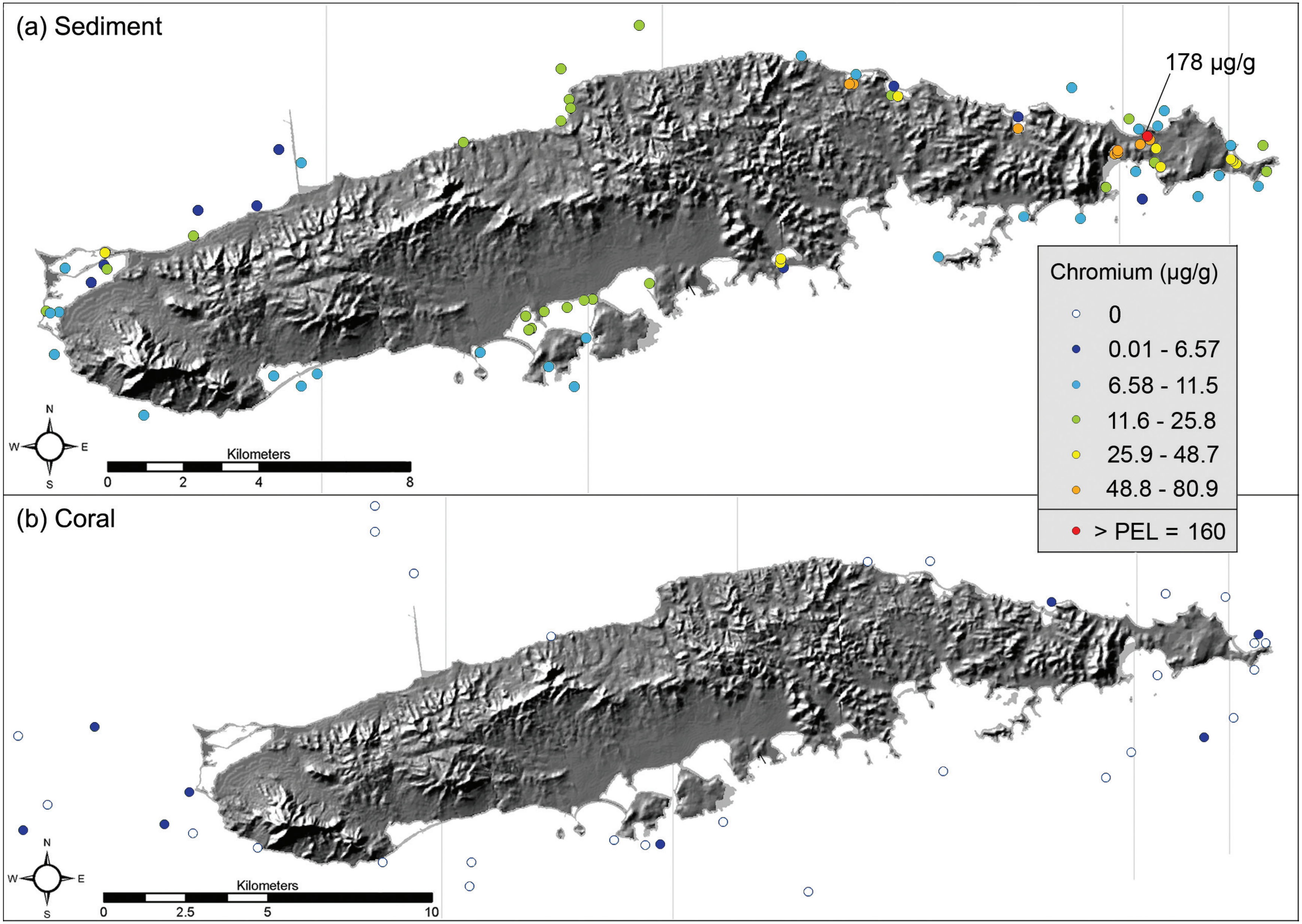


Figure 5.17. Chromium in sediments (a) and in *Porites astreoides* (b).

all occurred in or adjacent to the LIA (Figure 5.17a). The fifth location 22P, was an inland lagoon site on the north shore near Purple Beach (Figure 5.1).

Two sites in Vieques (52N4PX and 38P) exceeded the NS&T mean chromium concentration of 79.7 µg/g. The NS&T 85th percentile for chromium is 116 µg/g, and the only site sampled in Vieques to exceed this value was 52N4PX. Chromium is used to harden steel, is a component in a number of alloys, has widespread use in chrome plating, and has been a key metal used by the military and the aerospace industry in order to prevent corrosion and resist wear. Pait et al. (2007) detected a mean chromium concentration in the sediments in southwest Puerto Rico of approximately 31 µg/g, which included two sites within Guanica Bay that had fairly high (394 and 440 µg/g) chromium sediment values. If these two sites are removed in the calculation for southwest Puerto Rico, the mean is approximately 12 µg/g.

Summary for Chromium

- *The highest chromium concentration in the sediments was 178 µg/g and was found in Lagoon 7 in the former LIA.*
- *Concentrations of chromium were higher in the inland lagoon areas of the island.*
- *Sites in the northern half of Vieques had significantly higher chromium levels than those in the southern half of Vieques.*
- *The concentration of chromium in the sediments exceeded the ERL, TEL or AET threshold values at 11 sites. The threshold values indicate levels above which impacts may begin among sensitive life stages or species.*
- *The concentration of chromium in the sediments exceeded the Probable Effects Level or PEL at one site in Lagoon 7.*
- *The concentration of chromium in coral (Porites astreoides) was over two orders of magnitude lower than in sediments.*

Comparison Between Strata. A series of statistical tests were carried out to see how the concentration of chromium varied in the sediments across Vieques and if grain size was correlated with this trace element. As with cadmium, the concentration of chromium in the sediments was significantly higher in the inland lagoon areas ($p < 0.0001$). The inland lagoon sediments have a higher mean proportion (73%) of the finer grain sizes (silt and clays) compared with the nonlagoon sites (14%). As noted, metals are attracted to smaller grain sizes due to surface area and clay particle charge characteristics. A Wilcoxon nonparametric analysis indicated that chromium in the sediments did not vary ($p = 0.0591$) by stratum. A Wilcoxon test run to assess the differences in the concentration of chromium in the north versus the south strata, however, indicated a significant difference ($p = 0.0120$), with sites in the northern strata having higher concentrations of chromium. When the north and south strata were combined to make five strata in a west to east direction (Figure 5.7), a Wilcoxon test indicated no significant difference ($p = 0.0529$). Finally, a Spearman's ρ correlation coefficient was calculated to look at the association between chromium and % fines (clay + silt). The concentration of chromium was significantly correlated with the % fines ($p < 0.0001$).

Table 5.8. Chromium (Cr) in Vieques sediments and guidelines.

Vieques Results	Concentration (µg/g)
Vieques sediment Cr minimum	0
Vieques sediment Cr maximum	178
Vieques sediment Cr mean	22.5 ± 2.98
Vieques sediment Cr median	12.7
NOAA NS&T	
Mean	79.7 ±5.33
Median	66
85th Percentile	116.1
Guidelines	
Threshold Effects Limit (TEL)	52.3
Effects Range - Low (ERL)	81
Effects Range - Median (ERM)	370
Probable Effects Level (PEL)	160
Apparent Effects Threshold (AET)	62

Comparison Among Inland Lagoons. A nonparametric assessment of the nine inland lagoons indicated a significant difference ($p = 0.0041$) in the concentration of chromium in the sediments sampled. Pairwise comparisons of the ranked data indicated that Lagoon 6 and 7 adjacent to the LIA were significantly different (higher) from a number of the other lagoons (e.g., 1, 2, 3, 5, and 8).

Comparison with Sediment Quality Guidelines. A number of the sediment quality guidelines that have been established for chromium are shown in Table 5.8. There were eleven sites that exceeded the ERL, TEL or the AET. All three of these guidelines are threshold values below which effects are not expected

in benthic infaunal organisms. Concentrations between the ERL and ERM indicate that toxic effects could begin to appear in more sensitive species or life stages. Concentrations above the PEL or the ERM, however, indicate that effects are likely. The PEL is the geometric mean of the 50th percentile of the effects data and the 85th percentile of the no effects data used by MacDonald et al. (1996). The ERM is the 50th percentile concentration of the effects data used by Long et al. (1998). No sediments analyzed in this study exceeded the ERM for chromium. However, one sediment sample (52N4PX) exceeded the chromium PEL of 160 µg/g, indicating that this concentration was more likely to be impacting benthic infauna at this site.

<u>Chromium in Corals</u>. The concentration of chromium detected in the corals is shown in Figure 5.17b. The mean concentration was 0.18 ±0.06 µg/g, substantially below the mean sediment concentration of 22.5 µg/g (Table 5.6). Pait et al. (in press) did not detect chromium in any of the *P. astreoides* samples collected in southwest Puerto Rico, even though this trace element was found in all of the sediment samples. Additional work is needed to assess the relationship between chromium in sediments and uptake in corals. Also, no information was located on the effects of chromium in coral. This type of information would be useful not only for this study, but in other coral reef areas as well.

<u>Comparison with Other Work in Vieques</u>. Chromium has been documented in Vieques in other studies (ATSDR 2006; Barton and Porter 2004; CH2MHILL 2002; Massol-Deya et al. 2005; NOAA and Ridolfi 2006; CH2MHILL 2007). The chromium mean (22.5 µg/g) was below the threshold UTL range (70-72 µg/g) developed by CH2MHILL (2007), however, the chromium concentration at 52N4PX was above the UTL. Chromium observed by NOAA and Ridolfi (2006) in land crab (*C. guanhumi*) tissues across the island ranged from 1.15 – 5.71 µg/g. Barton and Porter (2004) observed chromium concentrations of 6.43 µg/g and 34.2 µg/g respectively in marine sediments adjacent to the scuttled *USS Killen* and inside a 55 gallon drum also adjacent to the scuttled ship. Neither of these concentrations exceed the sediment threshold guidelines in Table 5.8. The highest concentration of chromium detected was 182.6 µg/g by Massol-Deya et al. (2005) in plant organic material from the former LIA. This is similar to the highest observed sediment concentration (178 µg/g at 52N4PX) in the current study.

Copper. The concentration of copper quantified in the sediments and in coral tissues collected from Vieques is shown in Figure 5.18a and b, respectively.

<u>Copper in Sediments</u>. The mean concentration of copper found in the sediments was 25.9 ±3.15 µg/g (Table 5.9). The NS&T mean for sediment copper is 22.7 ±2.4 µg/g for the collection year 2006 and 2007, similar to the mean copper concentration found in the Vieques sediments.

Summary for Copper

- *The highest copper concentration in the sediments was 103 µg/g and was found in Lagoon 6, adjacent to the former LIA.*
- *Concentrations of copper were higher in the inland lagoon areas of the island.*
- *There were no differences in the concentration of copper in sediments between any of the strata.*
- *The concentration of copper in the sediments exceeded the threshold effects level (TEL) at 37 sites, and 28 sites where the ERL was exceeded. The threshold values indicate levels above which impacts may begin among more sensitive life stages or species.*
- *The mean concentration of copper in coral (<u>Porites</u> <u>astreoides</u>) was over an order of magnitude lower than in sediments.*

The highest concentration of copper found in the sediments in Vieques was 103 µg/g at 37P (Figure 5.1), an inland lagoon site located in the eastern end of Vieques near Bahia Salina del Sur on the southern shore, and adjacent to the former LIA. The second highest sediment concentration of copper (97.4 µg/g) was found in the same inland lagoon. The 10 highest concentrations of copper (Figure 5.18a and Appendix Q) were all located in inland lagoons, and were in either the former LIA or the Secondary Impact Area (SIA).

A total of 34 sediment samples taken in Vieques were above the NS&T Program mean for copper. Twenty-five sites were above the NS&T 85th percentile for copper of 38.3 µg/g. Twenty-one of these sites were in areas formerly controlled by the Navy. Four sites were in civilian areas. Copper has many applications including its use in wire, electronic circuits, antifouling paints for boat hulls, copper plumbing, industrial catalysts, and in a number of alloys (e.g., brass). Copper sulfate is used in agriculture and as an anti-algal agent, although it is probably unlikely copper was used to any great extent in this way in Vieques. Copper has also been used by the military in ordnance and in ammunition. The concentration of copper in the sediments collected from

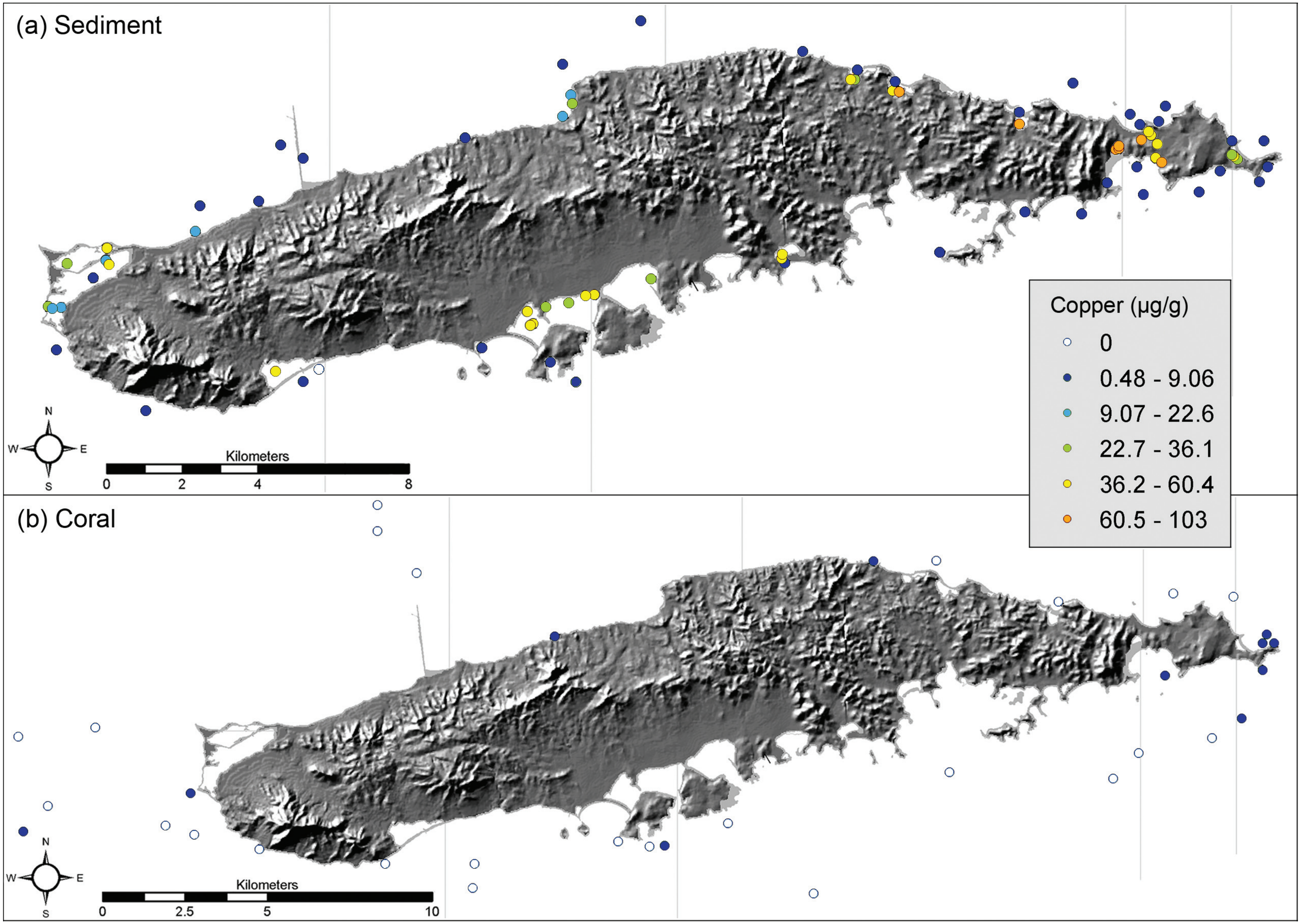


Figure 5.18. Copper in sediments (a) and in *Porites astreoides* (b).

Vieques can be compared with recent work in southwest Puerto Rico. Pait et al. (2007) found a mean copper concentration in the sediments of 5.21 µg/g, somewhat lower than the copper mean found in the sediments of Vieques.

Comparisons Between Strata. Nonparametric statistical tests (e.g., Wilcoxon) were used to assess how copper varied across the sites sampled in Vieques, and the relationship of copper to sediment grain size. As with the other trace elements, the concentration of copper in the sediments was significantly higher in the inland lagoon areas ($p < 0.0001$), which have a higher proportion of fine grained sediments than the nonlagoon areas. However, a Wilcoxon nonparametric analysis indicated that copper in the sediments did not vary ($p = 0.5260$) by stratum. Likewise, a Wilcoxon test run to assess the differences in the concentration of copper in the north versus the south strata, indicated no significant difference ($p = 0.7758$). Learned et al. (1973) noted anomalous concentrations of certain metallic elements including copper along the north coast of the island due to geologic processes, but those differences were not reflected statistically in the current study. In addition, a Wilcoxon test indicated no significant difference ($p = 0.2993$) in the concentration of copper in the sediments when the strata were combined to make a series of five strata in a west to east direction (Figure 5.7). A Spearman's ρ correlation coefficient did indicate that copper was significantly correlated with the % fines ($p < 0.0001$).

Comparison Among Inland Lagoons. A Wilcoxon nonparametric test indicated a significant difference ($p = 0.0192$) in the concentration of copper between the nine inland lagoons. A pairwise comparison (Tukey HSD) of the ranked data indicated that Lagoon 6 (Figure 5.7), located adjacent to the LIA had significantly higher copper concentrations than Lagoons 1, 2, and 9.

Comparison with Sediment Quality Guidelines. A number of sediment quality guidelines have been established for copper and are shown in Table 5.9. There were 37 sites that exceeded the TEL, and 28 sites that exceeded the ERL. There were no sites, however, where the sediment concentration exceeded the PEL, ERM, or AET. However, a copper concentration of 103 µg/g at 37P was just below the copper PEL.

Table 5.9. Copper (Cu) in Vieques sediments and guidelines.

Vieques Results	Concentration (µg/g)
Vieques sediment Cu minimum	0
Vieques sediment Cu maximum	103
Vieques sediment Cu mean	25.9 ± 3.15
Vieques sediment Cu median	12.2
NOAA NS&T	
Mean	22.7 ±2.4
Median	16
85th Percentile	38.3
Guidelines	
Threshold Effects Limit (TEL)	18.7
Effects Range - Low (ERL)	34
Effects Range - Median (ERM)	270
Probable Effects Level (PEL)	108
Apparent Effects Threshold (AET)	390

<u>Copper in Corals</u>. The concentration of copper found in the tissues of *P. astreoides* is shown in Figure 5.18b. The mean concentration was 0.76 ±0.26 µg/g, again substantially below the mean sediment concentration (Table 5.9). This lower detection of copper in the coral tissues can also be seen in Figure 5.18b. The highest copper concentration found in *P. astreoides* (6.5 µg/g) was at 5NEX1 (Figure 5.2) adjacent to the Eastern Conservation Area.

Effects of Copper on Corals. Copper is the trace element most commonly used in toxicity tests in corals. A number of studies have investigated the effects of this trace element on coral fertilization and development. Victor and Richmond (2005) found that a copper concentration of 10 µg/L and greater significantly affected fertilization in the reef building coral *Acropora surculosa* in the laboratory after five hours. They also found that embryo development was affected when gametes were exposed to copper at a concentration of 12 µg/L. At concentrations of 58 µg/L and higher, no embryo development was observed. Reichelt-Brushett and Michalek-Wagner (2005) investigated the effects of copper on the soft coral *Lobophytum compactum*. A significant difference in fertilization success was found at copper concentrations of 117 µg/L and above. Goh and Chou (1997) found that a copper concentration of 40 µg/L in the zooxanthellae *Symbiodinium microadriaticum*, isolated from the rice coral *Montipora verrucosa* inhibited growth in the symbiotic dinoflagellate. Goh and Chou (1997) also noted a synergistic effect when the zooxanthellae were exposed to both copper and zinc.

It should be understood that the concentrations of contaminants found in sediments cannot be directly compared with aqueous concentrations found to affect corals. The corresponding concentration of copper and many other contaminants in the water column is different, typically much less than the adjacent sediment con-

centration, however, these results indicate that when present in the aqueous phase at relatively low concentrations, copper can impact fertilization and development in corals.

Comparison with Other Work in Vieques. Copper has been documented in Vieques by numerous studies (ATSDR 2006; CH2MHILL 2002; Massol-Deya et al. 2005; NOAA and Ridolfi 2006; CH2MHILL 2007). CH2MHILL calculated a UTL for copper between 53 and 94 µg/g which is above the mean copper concentration found in the current study. The highest concentration of copper found in the sediments in the current study (103 µg/g), however, was above the UTL range. Copper observed by NOAA and Ridolfi (2006) in land crab tissues (*C. guanhumi*) across the island ranged from 26 – 179 µg/g. The highest concentration of copper was 203 µg/g, observed by ATSDR (2006) in fiddler crab tissues (*Uca sp.*) collected west of Laguna Kiani. ATSDR also found copper in fiddler crab tissue in the former LIA at a concentration of 180 µg/g. Both of these concentrations were higher than the copper detected in the sediments in this study. Comparison of data from different sources (i.e., crab tissue vs. sediments) can describe possible bioaccumulation effects as well as possible contamination in a different matrix.

Summary for Lead

- *The highest concentration of lead in the sediments was 17.6 µg/g at a site adjacent to the town of Isabel Segunda.*
- *Concentrations of lead were higher in the inland lagoon areas of the island.*
- *There was a difference in the concentration of lead in the sediments by strata, however, pairwise comparisons of the data failed to indicate differences between individual strata (e.g., North 5 versus South 1).*
- *None of the sediment lead concentrations exceeded any of the guidelines examined.*
- *The mean concentration of lead in coral (Porites astreoides) was nearly two orders of magnitude lower than in sediments.*

Lead. The concentration of lead in the sediments and in coral tissues collected in Vieques is shown in Figure 5.19 a and b, respectively.

Lead in Sediments. The mean concentration of lead found in the sediments in Vieques was 5.42 ±0.55 µg/g. The higher concentrations of lead appeared in a number of locations on the island, including sites within civilian areas, and sites within the former VNTR and NASD. The mean concentration of lead found in the sediments in Vieques can be compared with the rest of the Nation's coastal areas as sampled by the NS&T Program (Table 5.10). The NS&T mean for lead in sediments is 26.1 ±1.8 µg/g for the collection year 2006 and 2007, higher than the mean lead concentration found in the Vieques sediments.

Table 5.10. Lead (Pb) in Vieques sediments and guidelines.

Vieques Results	Concentration (µg/g)
Vieques sediment Pb minimum	0
Vieques sediment Pb maximum	17.6
Vieques sediment Pb mean	5.42 ± 0.55
Vieques sediment Pb median	1.29
NOAA NS&T	
Mean	26.1 ± 1.81
Median	22.3
85th Percentile	39.1
Guidelines	
Threshold Effects Limit (TEL)	30.24
Effects Range - Low (ERL)	46.7
Effects Range - Median (ERM)	218
Probable Effects Level (PEL)	112
Apparent Effects Threshold (AET)	400

The highest concentration of lead quantified in the sediments from Vieques was 17.6 µg/g at 16N2P, a site adjacent to the town of Isabel Segunda (Figure 5.1). The second highest lead sediment concentration (16.4 µg/g) was found at 45N3A, in Laguna Monte Largo. The NS&T 85th percentile for lead (39.1 µg/g) was more than two times greater than the highest lead concentration found in the sediments in Vieques.

Lead has many applications including lead-acid storage batteries, solder, bearings, electronics, various paints and primers, and in ammunition. Tetraethyl lead was used in the past as an anti-knock compound in gasoline. Pait et al. (2007) found a mean lead concentration in the sediments in southwest Puerto Rico of 1.93 µg/g, somewhat lower than the lead mean found in the sediments of Vieques.

Comparisons Between Strata. The nonparametric Wilcoxon test was used to assess how lead varied across the sites sampled in Vieques. The concentration of lead in the sediments was significantly higher in the inland

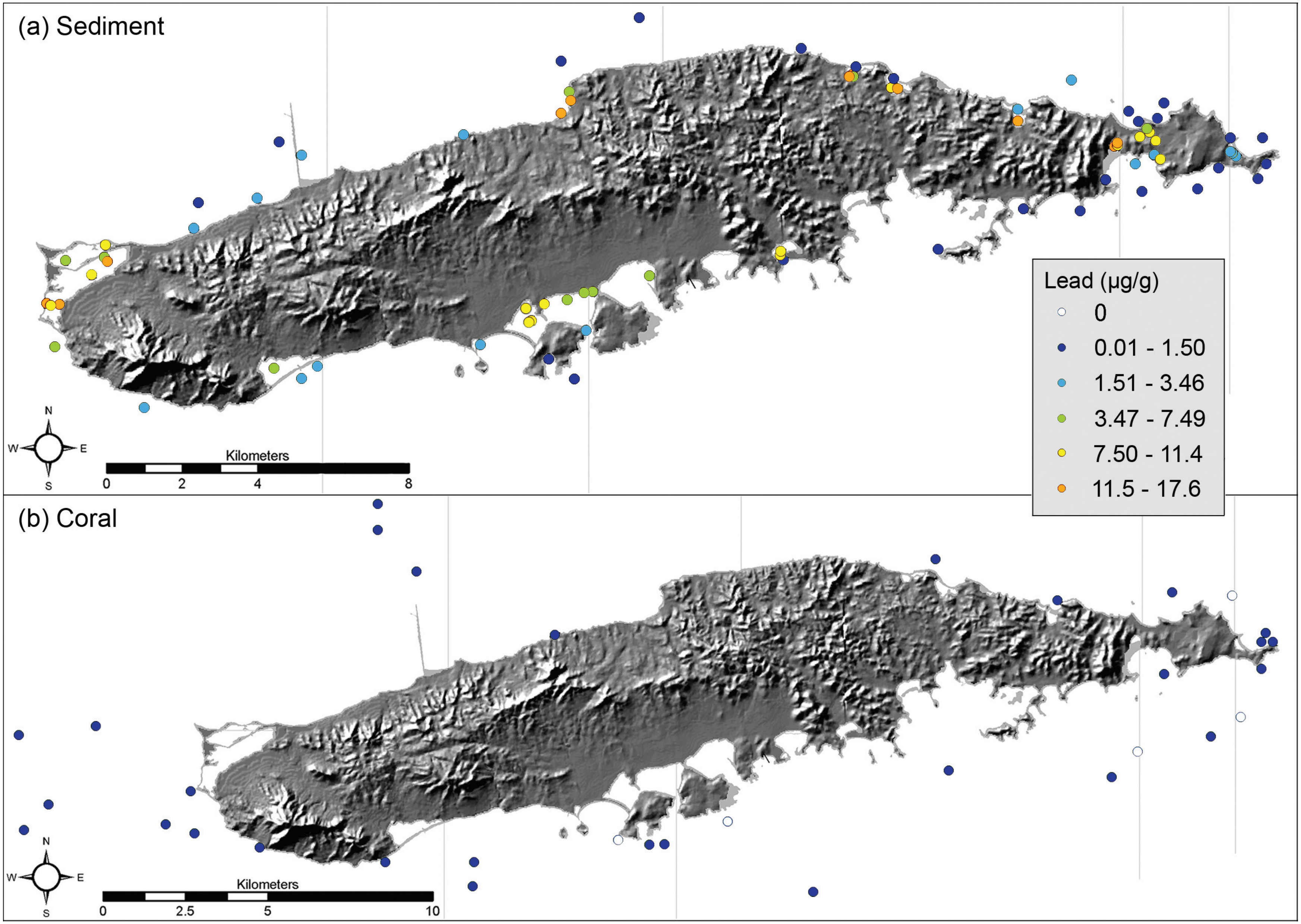


Figure 5.19. Lead in sediments (a) and in *Porites astreoides* (b).

lagoon areas ($p < 0.0001$), which have a higher proportion of fine grained sediments. Lead in the sediments also varied significantly ($p = 0.0465$) by stratum. A pairwise comparison of the ranked values, however, was not able to reveal any significant differences between individual strata. A Wilcoxon test run to assess the differences in the concentration of lead in the north versus the south strata indicated no significant difference ($p = 0.7989$). A Wilcoxon test indicated a significant difference ($p = 0.0496$) in the concentration of lead in the sediments when the strata were combined to make a series of five strata in a west to east direction (Figure 5.7). A pairwise comparison of the ranked data, however, did not reveal any significant differences. Finally, Spearman's ρ correlation coefficients were calculated to look at the association between lead and the % fines (clay + silt). The concentration of lead was significantly correlated with the % fines ($p < 0.0001$), indicating this trace element is associated with sediments containing higher levels of fine grained materials, including clays.

Comparison Among Inland Lagoons. A Wilcoxon nonparametric test indicated no significant difference ($p = 0.0754$) in the concentration of lead between the nine inland lagoons where the sampling strategy for the project enabled a comparison.

Comparison with Sediment Quality Guidelines. Some of the sediment quality guidelines that have been established for lead are shown in Table 5.10. None of the lead concentrations in the sediment samples from Vieques exceeded any of the guidelines examined.

Lead in Corals. The concentrations of lead found in the tissues of *P. astreoides* is shown in Figure 5.19b. The mean concentration was 0.07 ±0.01 µg/g, substantially below the mean sediment concentration (Table 5.10). The lower mean concentration of lead in coral tissues compared to the sediments can be seen in Figure 5.19 as well. The highest lead concentration found in *P. astreoides* (0.174 µg/g) was at 3N05 (Figure 5.2) near Punta Brigadier.

Effects of Lead on Corals. Reichelt-Brushett and Harrison (2005) looked at the effects of lead on a number of species of coral. The authors found that a lead concentration of 1,982 µg/L or above resulted in significantly reduced fertilization success in the finger coral *Acropora tennuis*. In *Acropora longicyathus*, lead concentrations of 855 µg/L or higher resulted in significantly reduced fertilization success.

Comparison with Other Work in Vieques. Lead has been documented in Vieques by a number of studies (ATSDR 2006; Barton and Porter 2004; CH2MHILL 2002; Massol-Deya et al. 2005; NOAA and Ridolfi 2006; CH2MHILL 2007). The UTL range for lead developed by CH2MHILL (2007) was 5.4 - 16 µg/g, and the mean lead concentration found in the sediments in the current study is at the low end of this range. Lead quantified by NOAA and Ridolfi (2006) in land crab tissues (*C. guanhumi*) across the island ranged from 0.02 – 2.55 µg/g, lower than the highest observed lead concentration in the current study. The highest concentration of lead observed in any matrix in Vieques (195 µg/g) was by Barton and Porter (2004) in brain coral tissues (*Diploria labyrinthiformis*) adjacent to underwater unexploded ordnance.

Other Trace and Major Elements in Sediments. A number of other trace and major elements were analyzed as part of the project in Vieques. Some of the results for sediments are briefly summarized below. With the exception of higher concentrations from inland lagoon sediments, few spatial differences were apparent. Aluminum, manganese, nickel and zinc were occasionally found at concentrations above threshold (e.g., AET and ERL) values.

Aluminum. The highest concentration of aluminum found in the sediments sampled in Vieques (118,000 µg/g) was from 45N3A, located in Laguna Monte Largo on the northern coast within the former VNTR. The mean concentration of aluminum in the sediments in Vieques (35,530 ±3,530 µg/g), was close to the UTL developed by CH2MHILL (2007), and below the NS&T mean aluminum value of 56,000 µg/g. As noted earlier, aluminum is a major crustal element, and so it is not surprising that concentrations are higher than a number of the other elements analyzed as part of this project. A Wilcoxon test indicated that aluminum was higher in the inland lagoon areas ($p < 0.0001$), but that the concentration of this major element was not significantly different between strata ($p = 0.0754$). There was also no significant difference in the concentration of aluminum in the north versus the south strata. When the strata were combined to create five west to east strata (Figure 5.7), a Wilcoxon test indicated a significant difference ($p = 0.0299$). Although the mean aluminum concentration in Stratum 3 was numerically higher, a pairwise comparison of the ranked values using a Tukey HSD test failed to reveal any significant differences for individual strata. An AET sediment guideline of 1.8% has been established for aluminum. The highest concentration of aluminum found in the sediments in Vieques was approximately 12%.

Arsenic. The mean concentration of arsenic in the sediments (4.37 ±0.33 μg/g) was below the NS&T mean value of 8.90 μg/g. The highest concentration of arsenic in the sediment samples from Vieques (15.4 μg/g) was from 27P in Lagoon 8 (Laguna Anones), located in the former LIA. A Wilcoxon test indicated that arsenic, however, was not higher in the inland lagoon areas ($p = 0.6003$), and that the concentration of arsenic was not significantly different between strata ($p = 0.1532$). There was also no significant difference in the concentration of arsenic in the north versus the south strata ($p = 0.1445$). When the strata were combined to create five west to east strata, a Wilcoxon test indicated no significant difference ($p = 0.2926$). The highest concentration of arsenic was below all the sediment quality guidelines examined.

Iron. Observations during visits to the former LIA revealed what appeared to be a significant amount of iron-containing fragments in the area. As a result, an analysis of data for this major element was carried out. The mean concentration of iron in the sediments for Vieques (17,610 ±1,920 μg/g), was below the NS&T mean value for iron of 24,600 μg/g. The highest concentration of iron in the sediments from Vieques (50,700 μg/g) was from 31N3P in Laguna Puerto Diablo. A Wilcoxon test indicated that iron was higher in the inland lagoon areas ($p < 0.0001$), but that the concentration was not significantly different between strata ($p = 0.4338$). There was also no significant difference in the concentration of iron in the north versus the south strata ($p = 0.5929$). When the strata were combined to create five strata in a west to east direction, a Wilcoxon test indicated no significant difference ($p = 0.3051$). An AET sediment guideline of 22% has been established for iron. The highest concentration of iron found in the sediments in Vieques was approximately 5%.

Manganese. The mean concentration of manganese in the sediments (301 ±31.8 μg/g), was below the NS&T mean manganese value of 608 μg/g. The highest concentration of manganese found in the sediments from Vieques (967 μg/g) was from 23P in Lagoon 4 (Laguna Algodones), located just west of Punta Brigadier. A Wilcoxon test indicated that manganese was higher in the inland lagoon areas ($p < 0.0001$), but that the concentration of manganese was not significantly different between strata ($p = 0.3695$). There was also no significant difference in the concentration of manganese in the north versus the south strata ($p = 0.3738$). When the strata were combined to create five west to east strata, a Wilcoxon test indicated no significant difference ($p = 0.5707$). The highest concentration of manganese in the sediments in Vieques was above the AET value of 260 μg/g.

Mercury. The mean concentration of mercury in the sediments (0.019 ±0.003 μg/g), was below the NS&T mean mercury value of 0.10 μg/g. The highest level of mercury (total) found in the sediments from Vieques (0.112 μg/g) was from 70S1P in Lagoon 1 (Laguna Boca Quebrada), located on the western end of Vieques. A Wilcoxon test indicated that mercury was higher in the inland lagoon areas ($p < 0.0001$), but that the concentration of mercury was not significantly different between strata ($p = 0.2797$). There was also no significant difference in the concentration of mercury in the north versus the south strata ($p = 0.3781$) or when the strata were combined to form five west to east strata ($p = 0.3545$). The highest concentration of mercury found in the sediments was less than the sediment quality guidelines examined.

Nickel. The mean concentration of nickel in the sediments (7.80 ±1.07 μg/g) was below the NS&T mean nickel value of 33 μg/g. The highest concentration of nickel (38.3 μg/g) was found at 52N4PX in Lagoon 7, located in the former LIA. A Wilcoxon test indicated that nickel was higher in the inland lagoon areas ($p < 0.0001$), but that the concentration of nickel was not significantly different between strata ($p = 0.2270$). There was also no significant difference in the concentration of nickel in the north versus the south strata ($p = 0.1790$), or when the strata were combined to form five west to east strata ($p = 0.5006$). The highest concentration of nickel found in the sediments was above the TEL (15.9 μg/g) and ERL (20.9 μg/g) threshold values.

Zinc. The mean concentration of zinc in the sediments (34.4 ±3.91 μg/g), was below the NS&T mean zinc value of 91 μg/g. The highest zinc concentration quantified in the sediments sampled in Vieques (130 μg/g) was from 36P in Lagoon 6 located in the area directly adjacent to the former LIA. As with a number of the other elements, A Wilcoxon test indicated that zinc was higher in the inland lagoon areas ($p < 0.0001$), however, the concentration of zinc was not significantly different between strata ($p = 0.2821$). There was also no significant difference in the north versus the south strata ($p = 0.4328$), or in the concentration of zinc when the strata were combined to form five west to east strata ($p = 0.2720$). The highest concentration of zinc found in the sediments was slightly above the threshold TEL (124 μg/g) value.

Radioactivity

At each inland lagoon site, two measurements of radioactivity were made. The first reading was made upon arrival at the site. The second reading was made of the sediment sample taken at the site. The results of the readings are included in Appendix S. The highest value recorded was 0.041 mR/hr at 02P; most of the readings ranged from 0 to 0.02 mR/hr. Background radiation at ground level is considered to be 0.021 mR/hr, and the upper limit for non-occupational exposure (including exposure of minors) is 0.063 mR/hr (CFR 2009). All inland lagoon sites and sediment samples were within the established background levels for radiation, or below the limit for non-occupational exposure.

Clostridium perfringens

This anaerobic, gram-positive staining rod-shaped bacteria frequently occurs in the intestines of humans as well as in domestic and wild animals. The results of the analysis of sediments for *C. perfringens* are shown in Appendix T. To assess the presence of viable *C. perfringens*, sediment extracts are plated on growth medium and the number of colonies that develop are counted. The highest concentration of *C. perfringens* (2,196 CFU/g) was found in 104S3P, an inland lagoon site adjacent to Bahia Mosquito. The second highest concentration was found at 46P also an inland lagoon site, adjacent to Blue Beach in the former Eastern Maneuver Area (Figure 5.1). Eight of the top 10 detections of *C. perfringens* occurred in inland lagoon areas. Sources of the elevated levels of *C. perfringens* include fecal material from humans, and from other animals including dogs, along with horses and cattle. Nonparametric analysis revealed that *C. perfringens* counts were higher in the inland lagoon areas than in nonlagoon areas (p = 0.0131). No other significant spatial differences were found. No health guidelines were located for *C. perfringens* in sediments. *C. perfringens* is a common cause of foodborne illnesses. A more severe form of the disease is often fatal and results from ingesting large numbers of the active bacteria. *C. perfringens* also has the capability of forming spores which can persist in soils and sediments.

Image 5.5. Rocky outcropping near a sampling site in the southern portion of the VNTR.

5.5 SUMMARY AND CONCLUSIONS

For this component of the Vieques ecosystem characterization, a total of 78 sediments and 35 coral (*Porites astreoides*) samples were collected in May and October 2007 using a stratified random sampling design. The island was divided into five north and five south strata. All samples were analyzed using protocols established by NOAA's National Status and Trends (NS&T) Program. Sediment samples were collected in waters from around the island, and also from a number of inland lagoons. Sediment and coral samples were analyzed for a suite of chemical contaminants including 58 polycyclic aromatic hydrocarbons (PAHs), 31 organochlorine pesticides, 38 polychlorinated biphenyls (PCBs), four butyltins, and 16 trace and major elements. The sediments were also analyzed for a suite of 15 energetics (explosives) and related compounds.

Overall, the concentrations of chemical contaminants found in the sediments and coral (*Porites astreoides*) tissues sampled from Vieques were low. Most sediment samples had contaminant concentrations below established effects guidelines. Contaminant concentrations in sediments from the inland lagoon areas were higher than in nonlagoon areas.

The sediment samples collected were also analyzed for a series of 15 energetics and related compounds. The initial analysis of the samples using EPA Method 8330, indicated possible detections at 14 sites. Subsequent reanalysis of the samples by EPA Method 8330 followed by LC/MS/MS (liquid chromatography/mass spectrometry/mass spectrometry) to confirm the presence and concentration of energetics in the 14 samples, however, revealed that none had detectable concentrations of the energetics analyzed.

As part of the data analysis, a series of statistical tests were run to assess how contaminants varied across the sites sampled on Vieques. Included were analyses to assess how the concentration of contaminants varied by strata, and comparisons between lagoon versus non-inland lagoon areas, north versus south strata, and when the north and south strata were combined, how the concentration of contaminants varied from west to east across the island in terms of former and current land use. The west to east strata corresponded to the Naval Ammunition Support Detachment (NASD) (1), the Civilian Area (2), the Eastern Maneuver Area/Secondary Impact Area (3), Live Impact Area (4), and the Eastern Conservation Area (5).

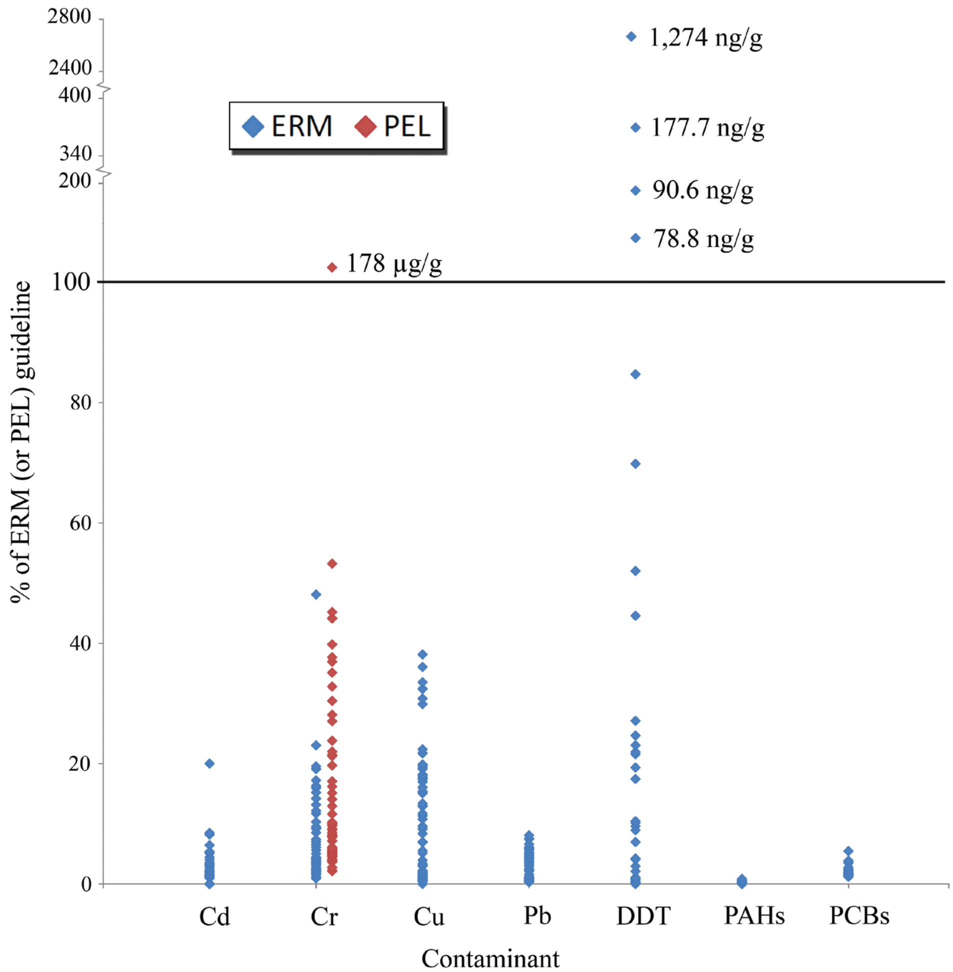


Figure 5.20. Summary of contaminants as a percent of the ERM (or the PEL) in sediments from Vieques.

There were only a few indications that concentrations of the sediment contaminants measured at some sites were likely to be toxic to sediment-inhabiting organisms. Only two contaminants in sediments appeared to be above concentrations that would indicate likely impacts to sediment-inhabiting organisms: total DDT and chromium. Using the NOAA Effects-Range Median (ERM) guideline (Figure 5.20), there were four sites that were above the DDT concentration that would indicate that toxicity to sediment-dwelling organisms was likely. The highest concentration of total DDT (1,274 ng/g) was found in a sediment sample taken from an inland lagoon site adjacent to Blue Beach, and was over an order of magnitude higher than the NOAA ERM guideline (46.1 ng/g) for total DDT. There were three other sediment samples above the ERM. Chromium exceeded (Figure 5.20) the Probable Effects Level (PEL) of 160 µg/g at an inland lagoon site located on the eastern end of Vieques near Bahia Icacos on the northern shore, in the former LIA. The concentration of chromium in the sediment sample was 178 µg/g, higher than the PEL, but below the NOAA ERM value of 370 µg/g.

Total DDT and lead varied by strata, but a pairwise comparison of the ranked data failed to show any differences between individual strata. No significant differences were found between the north and south strata, or the five strata moving west to east for total PCBs, butyltins, copper, arsenic, iron, manganese, mercury, nickel, or zinc. For total PAHs, higher concentrations were found in Stratum 1, corresponding to the NASD. For total DDT, sediment concentrations were higher in Stratum 3 which contains the site adjacent to Blue Beach (1,274 ng/g) that had the highest total DDT concentration measured in this study. For cadmium, Stratum 4, corresponding to the LIA had an overall higher sediment concentration. For chromium, the north strata had higher concentrations of this trace element, while the west to east strata (1 - 5) were not significantly different. A non-parametric test revealed differences in the lead concentration in the west to east strata, however, a comparison of the ranked values failed to reveal any statistical differences. For aluminum, Stratum 3 had significantly higher concentrations in the sediment.

The experimental design used in this study also allowed comparisons of contaminants between nine inland lagoons. Total PAHs were found to be significantly higher in Lagoon 1 (Laguna Boca Quebrada) than in some of the lagoons on the eastern part of the island. There were no differences in total PCBs between the nine

inland lagoons. For total DDT, Lagoon 4 (Laguna Algodones), Lagoon 5 near Blue Beach, and Lagoon 3 near Ensenada Sombe were higher than some of the inland lagoons further east on the island. Cadmium was higher in Lagoon 8 (Laguna Anones) in the LIA than in a number of the inland lagoons sampled on the west side of Vieques. Chromium was higher in Lagoons 6 and 7, in or adjacent to the former LIA. Copper was higher in Lagoon 6. There were no significant differences in the concentration of lead between the inland lagoons tested.

For corals, the concentration of total PAHs, total PCBs, total DDT, and butyltins were not significantly different from the sediments. For the trace and major elements, however, the concentration in coral tissues was usually lower than in sediments. The only element with significantly higher concentrations in coral tissues than in sediments was cadmium.

The results of this along with other characterizations can be used to assess the distribution and concentrations of chemical contaminants in sediments and coral tissues from around Vieques, and identify areas with possible contaminant-related issues. The information generated from this project can also be used to support and help guide the cleanup efforts on Vieques. Finally, the information presented here can serve as a baseline to document changes that may occur over time as restoration efforts proceed, and as some of the former U.S. Navy-owned areas undergo residential and commercial development.

ACKNOWLEDGEMENTS

A number of individuals and organizations on Vieques were instrumental to the success of this phase of the Ecological Characterization of Vieques. We would like to thank NOAA's Office of Response and Restoration (ORR) for funding this project. Oscar Diaz and Sandra Ortiz, both formerly with the Vieques National Wildlife Refuge provided us with unlimited access to their facility and discussions about Vieques. Mark Martin of the Vieques Conservation and Historical Trust graciously took us sampling in Bahia Mosquito, and provided us with invaluable background information on the bioluminescent bay. We would also like to thank Christopher Penny, NAVFAC, Vieques Munitions Response Program Manager; Madeline Rivera, NAVFAC, Vieques Field Office Site Manager; John Noles, NAVFAC, Restoration Sciences Support Section; and Carlton Finley, NAVFAC, for working with us to obtain the needed permissions and training to access the areas in the VNTR and the NASD. A number of US Navy UXO contractors enabled us to safely get to some of the more remote sampling sites on Vieques. In particular, we would like to thank David Green, Dennis Ballam, Mark Kelly, Ted Dingle and Chris Brown for their hard work and long hours. We would also like to thank Cliff Walden who came out with a lug wrench when the rental truck we were driving developed a flat tire. Divers Laurie Bauer, Randy Clark, Kimberly Edwards, Matt Kendall, Charles Menza, and Kimberly Woody assisted in the collection of sediment and coral samples. It was also great working with Diane Wehner and Jason Rolfe from ORR throughout the project. Finally, we would like to thank Captain Angel Nazario of the *Aquanauta* for his skill and patience in getting us to and from the dive sites.

LITERATURE CITED

ATSDR. 2001. Focused public health assessment: drinking water supplies and groundwater pathway evaluation, Isla de Vieques, Puerto Rico. Agency for Toxic Substances and Disease Registry, Federal Facilities Assessment Branch, Division of Health Assessment and Consultation; Atlanta, Georgia. October 16, 2001. Available at: http://www.atsdr.cdc.gov/HAC/PHA/vieques/vie_toc.html.

ATSDR. 2003a. Petitioned public health assessment, soil pathway evaluation, Isla de Vieques Bombing Range. Agency for Toxic Substances and Disease Registry, Federal Facilities Assessment Branch, Division of Health Assessment and Consultation. Available at: http://www.atsdr.cdc.gov/HAC/PHA/isladevieques/idv_toc.html. Last accessed 10 December 2008.

ATSDR. 2003b. Public health assessment, fish and shellfish evaluation, Isla de Vieques Bombing Range. Agency for Toxic Substances and Disease Registry, Federal Facilities Assessment Branch, Division of Health Assessment and Consultation. Available at: http://www.atsdr.cdc.gov/HAC/PHA/viequesfish/viequespr-toc.html#toc.

ATSDR. 2003c. Public health assessment, air pathway evaluation, Isla de Vieques Bombing Range. Agency for Toxic Substances and Disease Registry, Federal Facilities Assessment Branch, Division of Health Assess-

ment and Consultation. Available at: http://www.atsdr.cdc.gov/HAC/pha/vieques4/vbr_toc.html. Last accessed 31 August 2009.

ATSDR. 2006. Agency for Toxic Substances and Disease Registry. 2006.Health consultation: Land crab evaluation. National Oceanic and Atmospheric Administration Data. Isla de Vieques. U.S. Department of Health and Human Services, Agency for Toxic Substances and Disease Registry, Division of Health Assessment and Consultation. 22 pp.

Barton, J.V. and J.W. Porter. 2004. Radiological, chemical, and environmental health assessment of the marine resources of the Isla de Vieques Bombing Range, Bahia Salina del Sur, Puerto Rico. Underwater Ordinance Recovery, Inc. and the University of Georgia Institute of Ecology. 44 pp.

Batley, G. 1996. Distribution and fate of tributyltin. In: S. J. de Mora, editor, Tributyltin: A Case Study of an Environmental Contaminant. Cambridge University Press. Cambridge, England. 301 pp.

Becker, N.M. 1995. Fate of selected high explosives in the environment: a literature review. Los Alamos National Laboratory. Report LA-UR-95-1018. 19 pp.

Bennett, R.F. 1996. Industrial manufacture and applications of tributyltin compounds. In: S. J. de Mora (Ed.), Tributyltin: A Case Study of an Environmental Contaminant. Cambridge University Press. Cambridge, England. 301 pp.

Birch, G.F. 2003. A test of normalization methods for marine sediment, including a new post-extraction normalization (PEN) technique. Hydrobiologia 492: 5-13.

Birchenough, A.C., N. Barnes, S.M. Evans, H. Hinz, I. Kronke and C. Moss. 2002. A review and assessment of tributyltin contamination in the North Sea, based on surveys of butyltin tissue burdens and imposex/intersex in four species of neogastropods. Marine Pollution Bulletin 44: 534-543.

Burgess, R.M., S.A. Ryba, M.G. Cantwell and J.L. Gundersen. 2001. Exploratory analysis of the effects of particulate characteristics on the variation in partitioning of nonpolar organic contaminants to marine sediments. Water Research 35(18): 4390-4404.

CH2M HILL. 2000. Final expanded preliminary assessment/site investigation, U.S. Naval Ammunition Support Detachment. Department of the Navy, Atlantic Division, Norfolk, VA.

CH2M HILL. 2001. Final description of current conditions report, Atlantic Fleet Weapons Training Facility. Department of the Navy, Atlantic Division, Norfolk, VA.

CH2M HILL. 2002. Final soil, groundwater, surface water, and sediment background investigation report. October 16, 2002. Department of the Navy, Atlantic Division, Norfolk, VA.

CH2M HILL. 2004. Draft final, closure plan, open burn/open detonation site, former Atlantic Fleet Weapons Training Facility, Vieques, Puerto Rico. Prepared for Department of the Navy Atlantic Division Naval Facilities Engineering Command, Norfolk, VA. July 2004.

CH2MHILL. 2007. East Vieques background soil inorganics investigation report: former Vieques Naval Training Range, Vieques, Puerto Rico. Prepared for the Department of the Navy, NAVFAC Atlantic. Contract No. N62470-02-D-3052-CTO-039. 212 pp.

CH2MHILL and Baker Environmental, Inc. (Baker). 1999. Results of the hydrogeologic investigation: Vieques Island, Puerto Rico.

Code of Federal Regulations (CFR). 1998. PCB allowable uses provisions. 40 CFR 761.80, July 1998. Available at: http://www.access.gpo.gov/nara/cfr/cfr-table-search.html.

Code of Federal Regulations (CFR). 2009. Standards for protection against radiation. 10 CFR Ch. 1, Part 20, page 342, 1–1–09 Edition. Available at: http://www.access.gpo.gov/nara/cfr/cfr-table-search.html.

Decarlo, E.H., E. Cox, and M. Overfield. 2007. Ordnance Reef, Wai'anae, Hawai'i. Remote sensing survey and sampling at a discarded military munitions sea disposal site. Marine Sanctuaries Conservation Series NMSP-07-01. Silver Spring, MD. NOAA/NOS/National Marine Sanctuary Program. 98 pp.

Di Toro, D.M., C.S. Zarba, D.J. Hansen, W.J. Berry, R.C. Swartz, C.E. Cowan, S.P. Pavlou, H.E. Allen, N.A. Thomas and P.R. Paquin. 1991. Annual Review. Technical basis for establishing sediment quality criteria for nonionic organic chemicals using equilibrium partitioning. Environmental Toxicology and Chemistry 10:1541-1583.

Eisler, R. 1985. Cadmium hazards to fish, wildlife, and invertebrates: a synoptic review. U.S. Fish and Wildlife Service Biological Report 85(1.2). 30 pp.

Eisler, R. 1986. Chromium hazards to fish, wildlife, and invertebrates: a synoptic review. U.S. Fish and Wildlife Service Biological Report 85(1.6). 60 pp.

Eisler, R. 1987. Mercury hazards to fish, wildlife, and invertebrates: a synoptic review. U.S. Fish and Wildlife Service Biological Report 85(1.10). 63 pp.

Eisler. R. 1998. Copper hazards to fish, wildlife, and invertebrates: a synoptic review. U.S. Fish and Wildlife Service. Contaminant Hazard Reviews. Report No. 33. 120 pp.

El Nemr, A., A. El-Sikaily, A. Khaled, T.O. Said and A.M. Abd-Alla. 2004. Determination of hydrocarbons in mussels from the Egyptian Red Sea Coast. Environmental Monitoring and Assessment 96(1-3): 251-261.

Ellor, J.A., and Stemniski, P. 2007. Sustainable practices concerning the use of cadmium and hexavalent chromium as corrosion control products. Tri-Service Corrosion Conference 2007, Denver, CO. 8 pp.

EPA (U.S. Environmental Protection Agency). 1989. Evaluation of the apparent effects threshold (AET) approach for assessing sediment quality. Report of the Sediment Criteria Sub-committee. SAB-EETFC-89-027. Environmental Protection Agency. Washington, DC.

EPA (U.S. Environmental Protection Agency). 1997. Management of polychlorinated biphenyls in the United States. Environmental Protection Agency. Available at: http://www.chem.unep.ch/pops. Office of Pollution Prevention and Toxics, U.S. Environmental Protection Agency. 6 pp.

EPA (U.S. Environmental Protection Agency). 2009. DDT regulatory history: a brief survey (to 1975). Online: http://www.epa.gov/history/topics/ddt/02.htm. Last assessed 03 December 2009.

Gassman, N.J. and C.J. Kennedy. 1992. Cytochrome P-450 content and xenobiotic metabolizing enzyme activities in the scleractinian coral, *Favia fragum*. Bulletin of Marine Science 50(2): 320-330.

Gibbs, P.E. and G.W. Bryan. 1996. TBT-induced imposex in neogastropod snails: masculinization to mass extinction. In: S. J. de Mora, editor, Tributyltin: A Case Study of an Environmental Contaminant. Cambridge University Press. Cambridge, England. 301 pp.

Global Security. 2008. Explosives. GlobalSecurity.org. Available at: http://www.globalsecurity.org/military/systems/munitions/explosives.htm. Last accessed 03 June 2009.

Glynn, P.W., A.M. Szmant, E.F. Corcoran and S.V. Cofer-Shabica. 1989. Condition of coral reef cnidarians from Biscayne National Park reef tract: Pesticides, heavy metals and histopathological examination. National Park Service. Atlanta, Georgia. Southeast Regional Office. NTIS Order No.: PB90-17864/GAR.

Glynn, P.W., D.G. Rumbold and S.C. Snedaker. 1995. Organochlorine pesticide residues in marine sediment and biota from the northern Florida reef tract. Marine Pollution Bulletin 30(6): 397-402.

Goh, B.P.L. and L.M. Chou. 1997. Effects of the heavy metals copper and zinc on zooxanthellae cells in culture. Environmental Monitoring and Assessment 44:11-19.

Guzman-Martinez, M.D.C., P. Ramirez-Romero and A.T. Banaszak. 2007. Photoinduced toxicity of the polycyclic aromatic hydrocarbon, fluoranthene, on the coral, *Porites divaricata*. Journal of Environmental Science and Health, Part A 42(10): 1495-1502.

Hassett, J.J., J.C. Means, W.L. Banwart and S.G. Wood. 1980. Sorption related properties of sediments and energy related pollutants. U.S. Environmental Protection Agency. EPA-600/3-8-041. 133 pp.

Hoffsommer J.C. and Glover D.J. 1978. Explosives analyses of water and soil samples taken on Vieques Island, Puerto Rico. White Oak Laboratory, Silver Spring, MD: May 11-16 1978.

Hylland, K. 2006. Polycyclic aromatic hydrocarbons (PAH) ecotoxicology in marine ecosystems. Journal of Toxicology and Environmental Health, Part A 69: 109-123.

Kendall, M.S., C.R. Kruer, K.R. Buja, J.D. Christensen, M. Finkbeiner, R.A. Warner and M.E. Monaco. 2001. Methods used to map the benthic habitats of Puerto Rico and the U.S. Virgin Islands. NOAA Technical Memorandum NOS NCCOS CCMA 152. Silver Spring, MD. 45 pp.

Kennedy, C.J., N.J. Gassman and P.J. Walsh. 1992. The fate of benzo[a]pyrene in the scleractinian corals *Favia fragum* and *Montastrea annularis*. Marine Biology 113: 3131-318.

Kimbrough, K.L. and G.G. Lauenstein (eds). 2006. Major and trace element analytical methods of the National Status and Trends Program: 2000-2006. Silver Spring, MD. NOAA Technical Memorandum NOS NCCOS 29. 19 pp.

Kimbrough, K.L., G.G. Lauenstein and W.E. Johnson (eds). 2006. Organic contaminant analytical methods of the National Status and Trends Program: Update 2000-2006. NOAA Technical Memorandum NOS NCCOS 30. 137 pp.

Lai, M.G. 1978. Explosion products content of water and soil samples taken on Vieques Island, Puerto Rico. White Oak Laboratory, Silver Spring, MD: May 11-16 1978.

Lake, J.I., N.I. Rubenstein, H. Lee, C.A. Lake, J. Heltshe and S. Pevigano. 1990. Equilibrium partitioning and bioaccumulation of sediment-associated contaminants by infaunal organisms. Environmental Toxicology and Chemistry 9: 1095-1106.

Learned, R. E., G.R. Grove and R. Boissen. 1973. A geochemical reconnaissance of the Island of Vieques, Puerto Rico. US Geological Survey and Puerto Rico Department of Natural Resources. Open-file report 73-155 (order no. 1866). 84 pp.

Long, E.R., L.J. Field and D.D. MacDonald. 1998. Predicting toxicity in marine sediments with numerical sediment quality guidelines. Environmental Toxicology and Chemistry 17(4): 714-727.

Lopez, F. 2002. Contaminant levels in crabs from two SWMU and AOC Management Units on Vieques National Wildlife Refuge. U.S. Fish and Wildlife Service Report Number R4PRFO-02-0. U.S. Fish and Wildlife Service, Boqueron, Puerto Rico.

Lotufo, G.R. and M.J. Lydy. 2005. Comparative toxicokinetics of explosive compounds in sheepshead minnows. Ecotoxicology and Environmental Safety 49: 206-214.

MacDonald, D.D., R.S. Carr, F.D. Calder, E.R. Long and C.G. Ingersoll. 1996. Development and evaluation of sediment quality guidelines for Florida coastal waters. Ecotoxicology 5: 253-278.

Manahan, S.E. 1993. Fundamental of Environmental Chemistry. Lewis Publishers, Chelseaz, MI. 844 pp.

Massol-Deya, A., D. Perez, E. Perez, M. Berrios and E. Diaz. 2005. Trace elements analysis in forage samples from a US Navy bombing range (Vieques, Puerto Rico). International Journal of Environmental Research and Public Health 2 (2): 263-266.

McDonald, S.J., D.S. Frank, J.A. Ramirez, B. Wang and J.M. Brooks. 2006. Ancillary methods of the National Status and Trends Program: 2000-2006 Update. Silver Springs, MD. NOAA Technical Memorandums NOS NCCOS 28. 17 pp.

Miao, X.S., C. Swenson, K. Yanagihara and Q.X. Li. 2000. Polychlorinated biphenyls and metals in marine species from French Frigate Shoals, North Pacific Ocean. Archives of Environmental Contamination and Toxicology 38(4): 464-471.

Naval Facilities Engineering Command (NAVFAC). 2007. Ecological risk assessment tier 1 screening DRAFT. supplemental RI at Operable Unit 2. Department of the Navy. Naval Facilities Engineering Command Northwest. Bremerton, Washington. 66 pp.

Neff, J.M. 1985. Polycyclic aromatic hydrocarbons. In: G.M. Rand and S.R. Petrocelli. Fundamentals of Aquatic Toxicology. Hemisphere Publishing Corporation. New York. 666 pp.

Negri, A.P., L.D. Smith, N.S. Webster and A.J. Heyward. 2002. Understanding ship-grounding impacts on a coral reef: potential effects of anti-foulant paint contamination on coral recruitment. Marine Pollution Bulletin 44: 111-117.

Negri, A.P. and A.J. Heyward. 2001. Inhibition of coral fertilisation and larval metamorphosis by tributyltin and copper. Marine Environmental Research 51: 17-27.

NOAA (National Oceanic and Atmospheric Administration). 1993. Sampling and analytical methods of the National Status and Trends Program National Benthic Surveillance and Mussel Watch Projects. 1984-1992. Volume I. Overview and summary of methods. G.G. Lauenstein and A.Y. Cantillo, editors. NOAA Technical Memorandum NOS ORCA 71. 117 pp.

NOAA (National Oceanic and Atmospheric Administration). 1998. NS&T Program: National Status and Trends Program for Marine Environmental Quality. NOAA/National Ocean Service, 32 pp.

NOAA and Ridolfi. 2006. Final data report for the Vieques Island biota sampling project, Vieques Island, Puerto Rico. National Oceanic and Atmospheric Administration (NOAA) Office of Response and Restoration and RIDOLFI Inc. Seattle, WA.

Pait, A.S., D.R. Whitall, C.F.G. Jeffrey, C. Caldow, A.L. Mason, J.D. Christensen, M.E. Monaco and J. Ramirez. 2007. An assessment of chemical contaminants in the marine sediments of southwest Puerto Rico. NOS NCCOS 52. Silver Spring, MD. NOAA/NOS/Center for Coastal Monitoring and Assessment. 116 pp.

Pait, A.S. C.F.G. Jeffrey, C. Caldow, D.R. Whitall, S. Ian Hartwell, A.L. Mason and J.D. Christensen. In press. Chemical contamination in southwest Puerto Rico: a survey of contaminants in the coral *Porites astreoides.* Caribbean Journal of Science.

Peachey, R.L. and D.G. Crosby. 1996. Phototoxicity in tropical reef animals. Marine Environmental Research 42(1-4): 359-362.

Readman, J.W., I. Tolosa, A.T. Law, J. Bartocci, S. Azemard, T. Hamilton, L.D. Mee, A. Wagener, M. Le Tissier, C. Roberts, N. Downing and A.R.G. Price. 1996. Discrete bands of petroleum hydrocarbons and molecular organic markers identified within massive coral skeletons. Marine Pollution Bulletin 32:437-443.

Reichelt-Brushett, A.J. and P.L. Harrison. 1999. The effect of copper, zinc and cadmium on fertilization success of gametes from scleractinian reef corals. Marine Pollution Bulletin 38: 182-187.

Reichelt-Brushett, A.J. and P.L. Harrison. 2005. The effect of selected trace elements on the fertilization success of several scleractinian coral species. Coral Reefs 24: 524-534.

Reichelt-Brushett, A.J. and K. Michalek-Wagner. 2005. Effects of copper on the fertilization success of the soft coral *Lobophytum compactum*. Aquatic Toxicology 74: 280-284.

Rosen, G. and G.R. Lotufo. 2005. Toxicity and fate of two munitions constituents in spiked sediment exposures to marine amphipod *Eohaustorius estuarius*. Environmental Toxicology and Chemistry 24:2887-2897.

Rosen, G. and G.R. Lotufo. 2007. Toxicity of explosive compounds to the marine mussel, *Mytilus galloprovincialis*, in aqueous exposures. Ecotoxicology and Environmental Safety 68: 228-236.

Shine, J. and G. Wallace. 2000. Chemical aspects of organic carbon and ecosystem stress in benthic ecosystems. In: Ad Hoc Benthic Indicator Group - results of initial planning meeting. IOC Technical Series No 57. UNESCO. 65 pp.

Solbakken, J.E., A.H. Knap, T.D. Sleeter, C.E. Searle and K.H. Palmork. 1984. Investigation into the fate of 14C-labeled xenobiotics (napthalene, phenanthrene, 2,4,5,2',4',5'-hexachlorobiphenyl, octachlorostyrene) in Bermudian corals. Marine Ecology Progress Series 16: 149-154.

Thomas, S.D. and Q.X. Li. 2000. Immunoaffinity chromatography for the analysis of polycyclic aromatic hydrocarbons in corals. Environmental Science & Technology 34(12): 2649-2654.

U.S. Army Corps of Engineers (USACOE). 2008. Final baseline ecological risk assessment report, former Raritan Arsenal, Edison, New Jersey. W.O. No 03886.110.301.0005. Weston Solutions, Inc.

U.S. Department of Human Health and Services (USDHHS). 1995. Polycyclic aromatic hydrocarbons toxicology profile. Agency for Toxic Substance and Disease Registry (ATSDR). Atlanta, GA. 487 pp.

U.S. Department of Human Health and Services (USDHHS). 1999. Toxicological profile for cadmium. Agency for Toxic Substance and Disease Registry (ATSDR). Atlanta, GA. 439 pp.

Victor, S. and R.R. Richmond. 2005. Effect of copper on fertilization success in the reef coral *Acropora surculosa*. Marine Pollution Bulletin 50: 1433-1456.

CHAPTER 6: CHARACTERIZATION OF SPATIAL AND TEMPORAL NUTRIENT DYNAMICS

David R. Whitall[*], Andrew L. Mason, Anthony S. Pait, Varis Ransibrahmanakul, and John D. Christensen

Center for Coastal Monitoring and Assessment, National Centers for Coastal Ocean Science, National Ocean Service, NOAA, 1305 East-West Hwy, Silver Spring, MD 20910

[*]*Corresponding author: dave.whitall@noaa.gov*

6.1 INTRODUCTION

Primary productivity in marine systems is most often limited by nitrogen (N), but phosphorus (P) can be co-limiting under certain circumstances and systems can vary from N limitation to P limitation over space and time. In estuarine systems, nutrient enrichment can result in algal blooms, changes in algal community composition (including harmful algal blooms) and increases in hypoxia/anoxia (Bricker et al. 2007). In Vieques, lagoon ecosystems are of ecological significance, ranging from bird, fish and crab habitats to the unique dinoflagellate populations of the bioluminescent bay. Furthermore, in tropical systems, excess nutrient loads can cause increases in macroalgal growth and can have deleterious effects on corals, such as macroalgae outcompeting and overgrowing corals. Finally, nitrogen and phosphorus can impact corals directly by lowering fertilization success (Harrison and Ward 2001), and reducing both photosynthesis and calcification rates (Marubini and Davis 1996).

Land based contributions of nutrients come from a variety of sources. Phosphorus and reactive nitrogen can enter the environment from chemical fertilizer (agriculture, lawns, golf courses), industrial sources, animal waste, and human waste (Galloway et al. 2003). Additionally, nitrogen can be contributed from biological nitrogen fixation and atmospheric nitrogen deposition (originating from fossil fuel combustion and ammonia volatilization from agriculture) (Mathews et al. 2002).

Although a comprehensive island wide nutrient budget is beyond the scope of this study, it seems likely that human waste is the largest contributor to the nutrient budget on the island due to a lack of significant agricultural activity and no industrial sources on the island. The wastewater treatment plant (WWTP) in Vieques performs secondary sewage treatment and has a capacity of 0.5 MGD (Navarro 2002). The WWTP is located on the north shore of the island, west of Esperanza and east of the airport (Figure 6.1). Effluent from the WWTP is discharged to a treatment lagoon system consisting of four evaporation/percolation cells, which have no discharge point to the surface waters (NOAA 2007). This type of system relies on a combination of evaporation/volatilization to the atmosphere and a percolation of treated liquid into the groundwater. Volatilization of ammonia from the lagoon system may result in atmospheric deposition of ammonia to the landscape and coastal waters. This singular facility serves a population of 4,000 (less than half the population of the

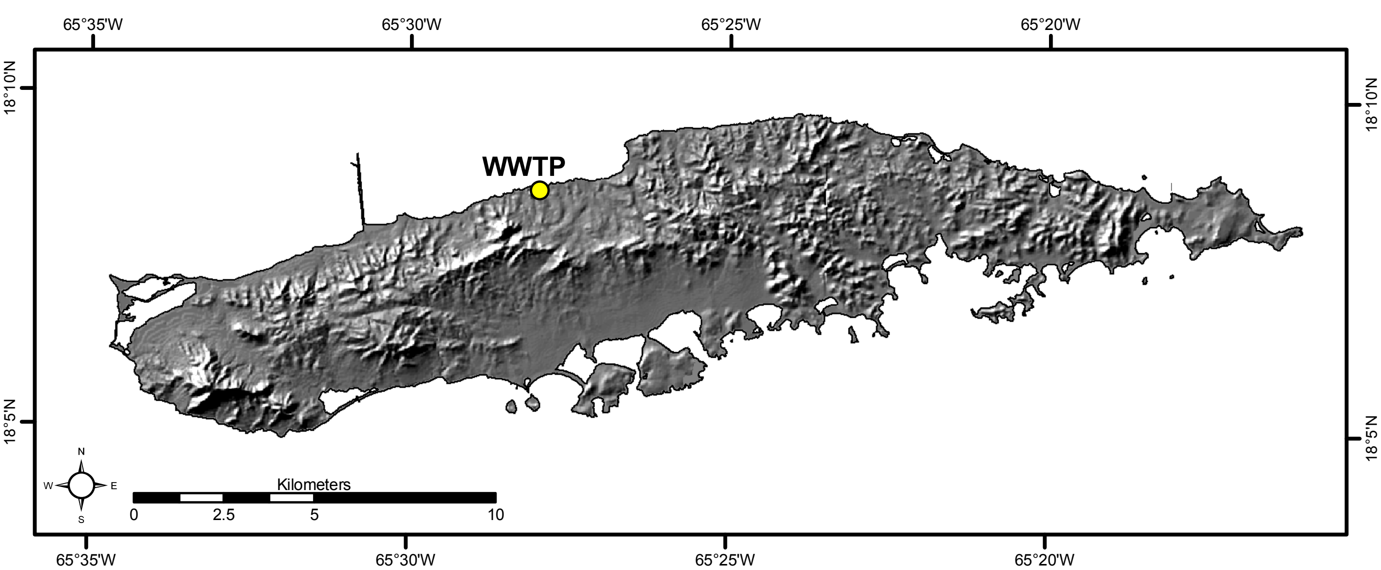


Figure 6.1. Location of wastewater treatment plant (WWTP) site.

island) with the rest of the population not being served by a WWTP. This unsewered population may be especially important to the nutrient budgets of the island.

As the economy of Vieques shifts from being centered around the activities of the U.S. Navy towards tourism, significant development is expected to occur. With development comes the potential for increased nutrient loads. These sources could include increased human waste (with population increases) and increased fertilizer inputs (from golf courses and lawns).

The goals of this part of the ecological characterization project of Vieques were to:

1) Determine if there are any hotspots of nutrient enrichment in the coastal waters;

2) Establish a baseline of nutrient condition against which to measure changes in the future;

3) Characterize the spatiotemporal variability in nutrient concentrations;

4) Characterize the spatiotemporal variability in chlorophyll and turbidity using remote sensing technologies.

6.2 METHODS

Sampling Design

An initial sampling survey of nutrients was conducted in May 2007, in conjunction with the sediment and coral sampling described in previous chapters. Nutrient samples were taken at 138 randomly selected sites. These sites were randomly stratified based on habitat and longitude, as described previously. Results from this initial sampling (Figure 6.2, 6.3) were used to inform a stratified random sampling design for subsequent sampling efforts. Results from the initial sampling suggested that the lagoons were much higher in nutrients than other sites. Because water column nutrient concentrations can vary greatly from season to season, and are often driven by watershed runoff, sampling was conducting in July, August, September, October, November of 2007, and February and March of 2008. The February and March sampling occurred during the dry season, whereas the other sampling dates were during the wet season (Figure 6.4). Forty stratified random sampling sites were selected (Figure 6.5). These samples were stratified by location: inshore (<1.5 km from shore), offshore (>1.5 km from shore) and lagoons, and were evenly distributed between the eastern (uninhabited) and western (inhabited) halves of the island. Due to weather and boat related problems, not all sites could be sampled at every time point. A total of 193 samples were collected during the assessment period.

Sample collection methods

Nutrient samples were collected in high density polyethylene (HDPE) bottles from 0.1 m below the surface. In extremely shallow lagoons (<0.5 m), samples were taken at half the distance to the bottom; in this situation, care was taken to exclude sediment from the samples. Bottles were rinsed three times with site water prior to sampling. Nitrile or latex gloves were worn by field personnel to avoid contamination of the samples during handling. On each sampling mission, replicate samples were collected at four (randomly selected) of the 40 sites to ensure precision in methodology. After collecting the samples, additional data (salinity, temperature, dissolved oxygen) were collected with a YSI 85 handheld water quality meter. Samples were stored on ice, in the dark while in the field and frozen at -20° C upon returning to the lab and not thawed until immediately prior to analysis. Samples were not filtered so that total nutrient levels could be analyzed, rather than only dissolved levels.

Analytical methods used for the analysis of nutrients in water

TDI-Brooks International conducted the nutrient laboratory analyses. Water samples were analyzed for a standard suite of nutrient analytes: nitrate (NO_3^-), nitrite (NO_2^-), orthophosphate ($HPO_4^=$), ammonium (NH_4^+), urea ($(NH_2)_2CO$), total nitrogen and total phosphorus (Table 6.1).

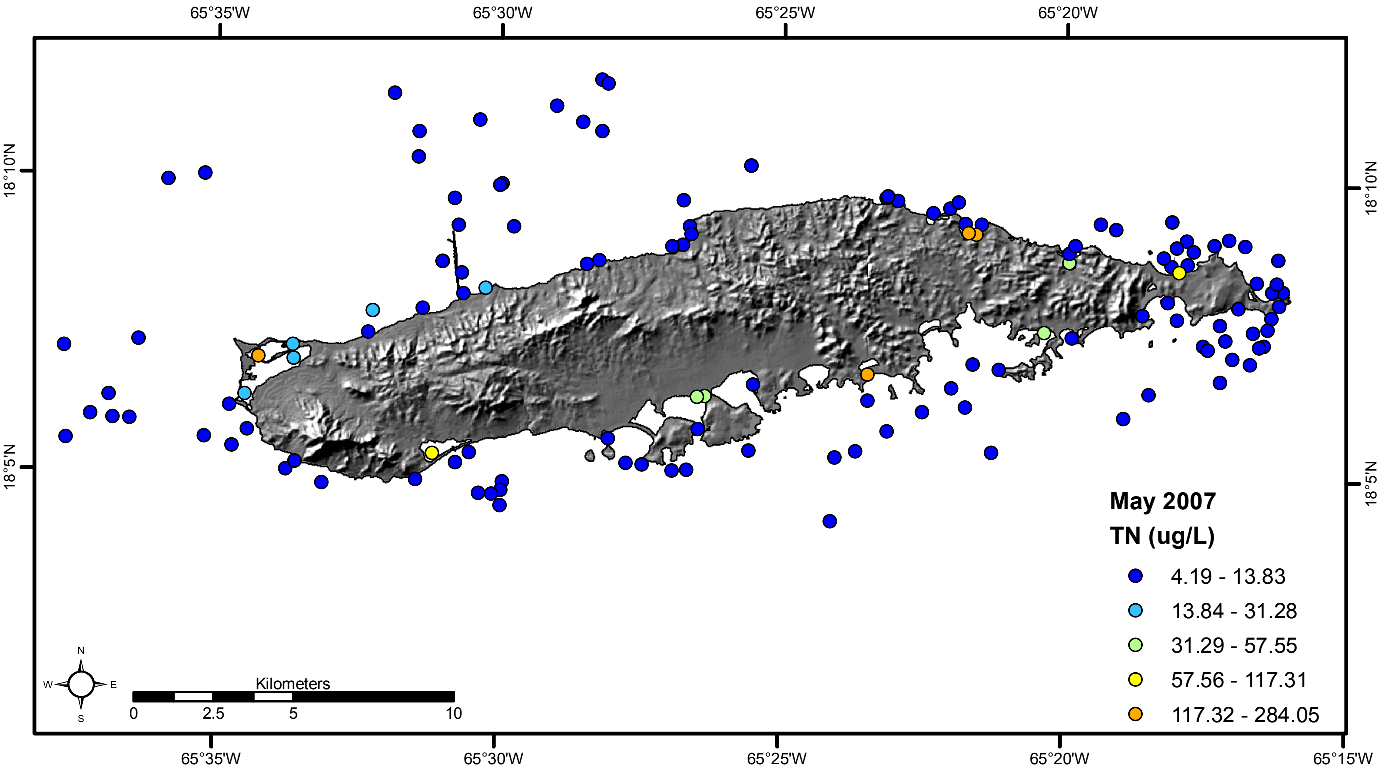


Figure 6.2. Preliminary sampling for total nitrogen (TN) in May 2007.

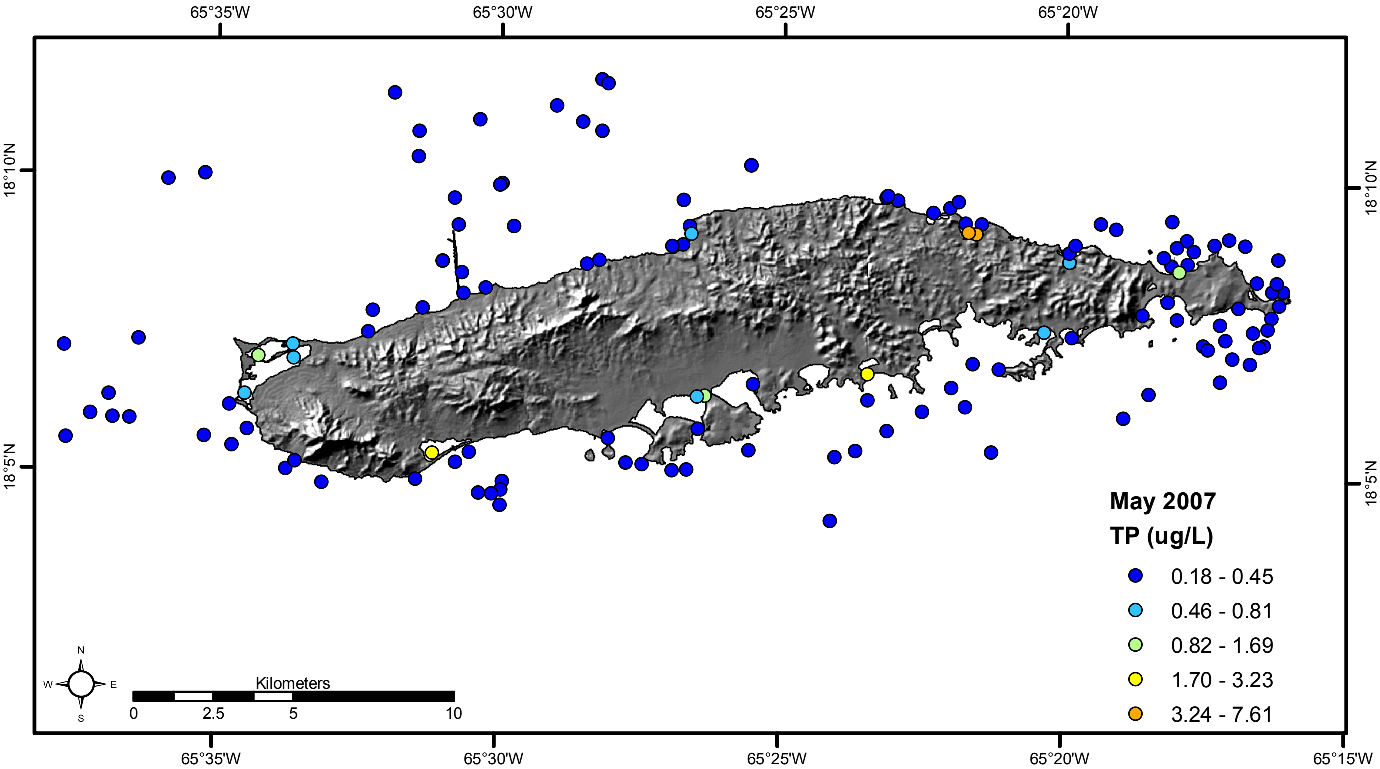


Figure 6.3. Preliminary sampling for total nitrogen (TP) in May 2007.

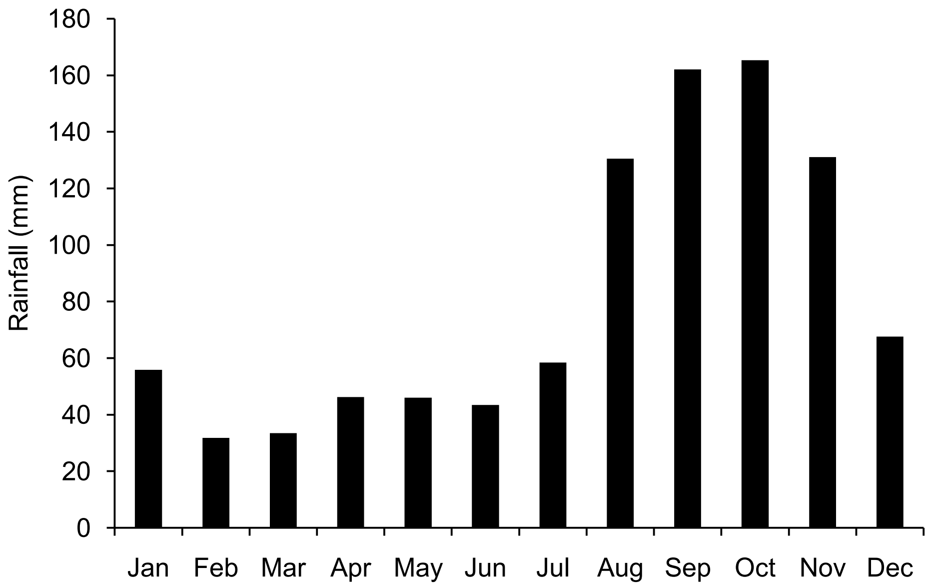


Figure 6.4. Average monthly precipitation in Vieques from 1971-2000 (most recent available data). From: http://cirrus.dnr.state.sc.us/cgi-bin/sercc/cliMAIN.pl?pr9763.

Table 6.1. Details on analytical methods for nutrients

Analyte	Method Detection Limit (µM)	Method Detection Limit (mg/L)	Standard Range (µM)	Standard Range (mg/L)
NO_3^-	0.177	0.010	3.85 - 30.14	0.23 - 1.86
NO_2^-	0.010	0.0004	0.09 - 0.72	0.006 - 0.033
$HPO_4^=$	0.030	0.002	0.35 - 2.18	0.021 - 0.21
$HSIO_3^-$	0.155	0.014	4.05 - 30.08	0.25 - 2.80
NH_4^+	0.070	0.001	0.42 - 3.44	0.026 - 0.062
Urea	0.205	0.012	0.59 - 4.42	0.036 - 0.265

Nitrate and nitrite analyses were based on the methodology of Armstrong et al. (1967). Orthophosphate was measured using the methodology of Bernhardt and Wilhelms (1967) with the modification of hydrazine as reductant. Silicate determination was accomplished using the methods of Armstrong et al. (1967) using stannous chloride. Ammonium analysis was based on the method of Harwood and Kuhn (1970) using dichloro- isocyanurate as the oxidizer. Urea was measured using diacetyl-monoximine and themicarbozide. The total concentrations of nitrogen and phosphorus were determined after an initial decomposition step. This method involves persulfate oxidation while heating the sample in an autoclave (115°C, 20 minutes) (Hansen and Koroleff 1999). After oxidation of the samples, nutrient determination was conducted on the Technicon II analyzer for nitrate and orthophosphate.

Because data were not normally distributed (Shapiro-Wilk W test), non-parametric statistics (Wilcoxon test, α=0.05) were used to evaluate differences between strata and between seasons.

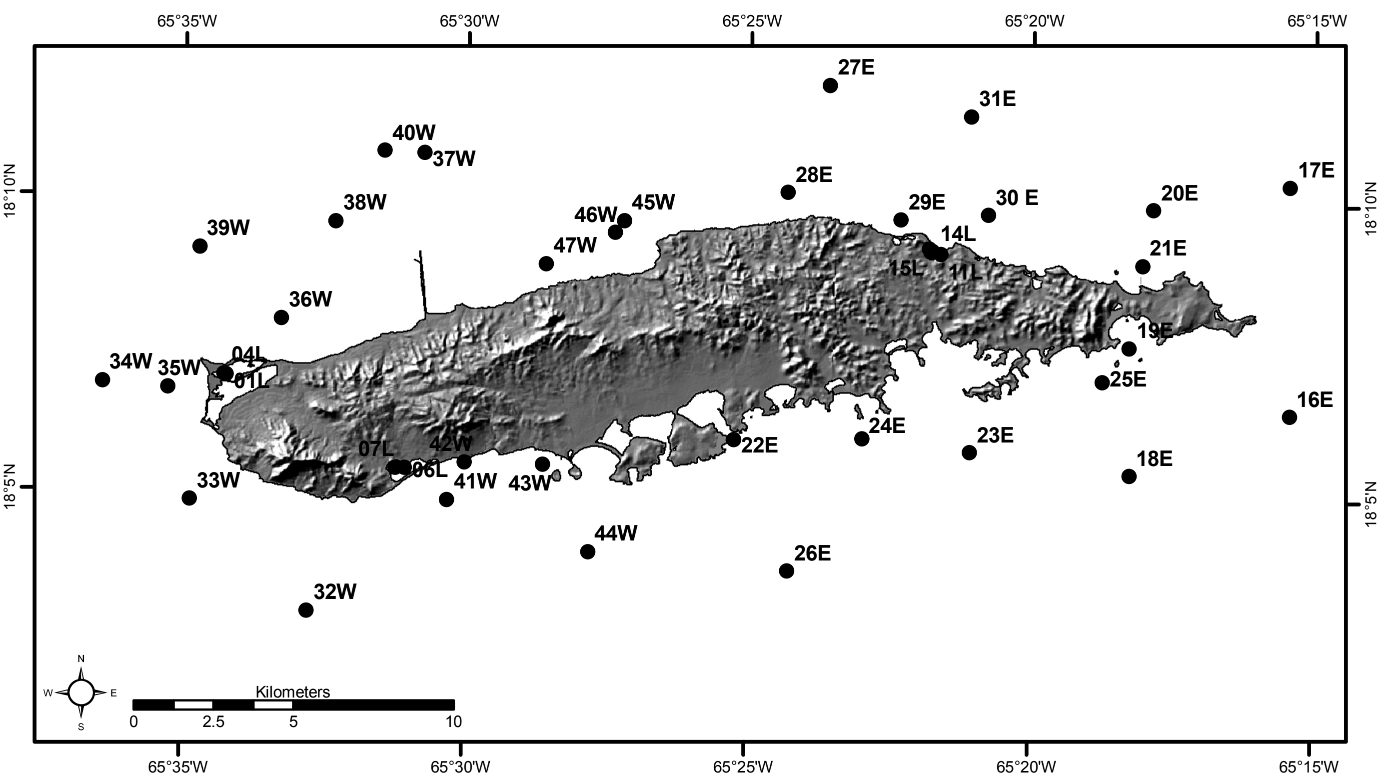


Figure 6.5. Location of sampling sites.

6.3 RESULTS AND DISCUSSION

Summary statistics for all analytes are shown in Tables 6.2a and 6.2b. Data were segregated by lagoon and inshore/offshore because the lagoons are extremely different systems (based on both qualitative observations and water quality/nutrient data) from the nearshore and offshore waters.

Table 6.2a. Lagoon nutrient summary statistics (July 2007 to March 2008). Concentrations in ug/L.

Analyte	Mean	Standard deviation	Minimum	Maximum
HPO_4	30.1	20.6	2.1	112.0
TP	106.8	91.0	2.4	556.7
NH_{4+}	17.2	11.2	1.1	48.8
NO_{3-}	2.7	2.6	0.04	13.5
NO_{2-}	1.7	1.0	0.03	5.0
Urea	31.2	35.5	4.4	172.4
TN	2810.4	1624.9	218.4	7331.4

Table 6.2b. Coastal (inshore and offshore) nutrient summary statistics (July 2007 to March 2008). Concentrations in ug/L.

Analyte	Mean	Standard deviation	Minimum	Maximum
HPO_4	4.3	2.8	1.2	11.5
TP	5.7	2.2	0.5	13.8
NH_{4+}	1.9	1.9	0.06	11.2
NO_{3-}	3.6	1.8	0.04	1.1
NO_{2-}	0.5	0.3	0.04	1.1
Urea	6.0	3.7	1.8	25.2
TN	131.3	229.7	83.6	2766.4

Precipitation Data

Precipitation data during the study period were acquired from the RAWS USA Climate Archive (Desert Research Institute 2009) for the station in Vieques (18° 07' 18", 65° 24' 58"). Precipitation can generate nutrient laden runoff which can be an important driver of nutrient concentrations in some systems.

General Spatial Patterns

In general, maximum observed nutrient concentrations at each site were highest in the lagoons (Figures 6.6-6.11). There were two sites off the south central coast where maximum observed nitrate plus nitrite was also relatively high (Figure 6.6), but it is unclear why these sites had high concentrations. Mean nutrient concentrations were also highest in the lagoons (Figures 6.12-6.17). There were no clear spatial patterns between the eastern (uninhabited) and western (inhabited) sides of the island for either maximum or mean concentrations (Figures 6.6-6.17).

Spatial Patterns by Strata

There were no significant differences among strata for orthophosphate, with higher concentrations of total phosphorus (TP) in the offshore waters than the inshore waters (Figure 6.18). This is somewhat unexpected, but may represent higher uptake of phosphorus by nearshore primary producers. For all nitrogen species, mean concentrations in lagoon samples were an order of magnitude higher and significantly different than either inshore or offshore sites (Figure 6.19). It is likely that these are the natural condition of the lagoons. The lagoons are shallow, poorly flushed and visibly high in humic materials. The lagoons are high in organic matter from the fringing mangroves, and submerged aquatic vegetation (Image 6.1) or benthic microbial mats. There are no statistically significant differences between inshore and offshore nitrogen concentrations (Figure 6.19). This would suggest that, island-wide, there is not a strong land based source of nutrients. Further evidence of this can be seen when comparing the eastern end of the island, which is uninhabited, to the western end of the island, which is inhabited. There are no significant differences in nutrient concentrations between the eastern and western ends of the island, except for urea which is higher in the western zone (Figures 6.20 and 6.21). If anthropogenic land based sources of pollution made up an important portion of the nutrient budget, nutrient concentrations would be expected to be higher on the western end of the island, where the human population resides. Higher concentrations are only seen on the western side of the island for urea. This may represent a human or animal signal, but more investigation would be required to determine why this pattern is not observed in other nutrient species.

Image 6.1 Submerged aquatic vegetation mat in lagoon on Vieques.

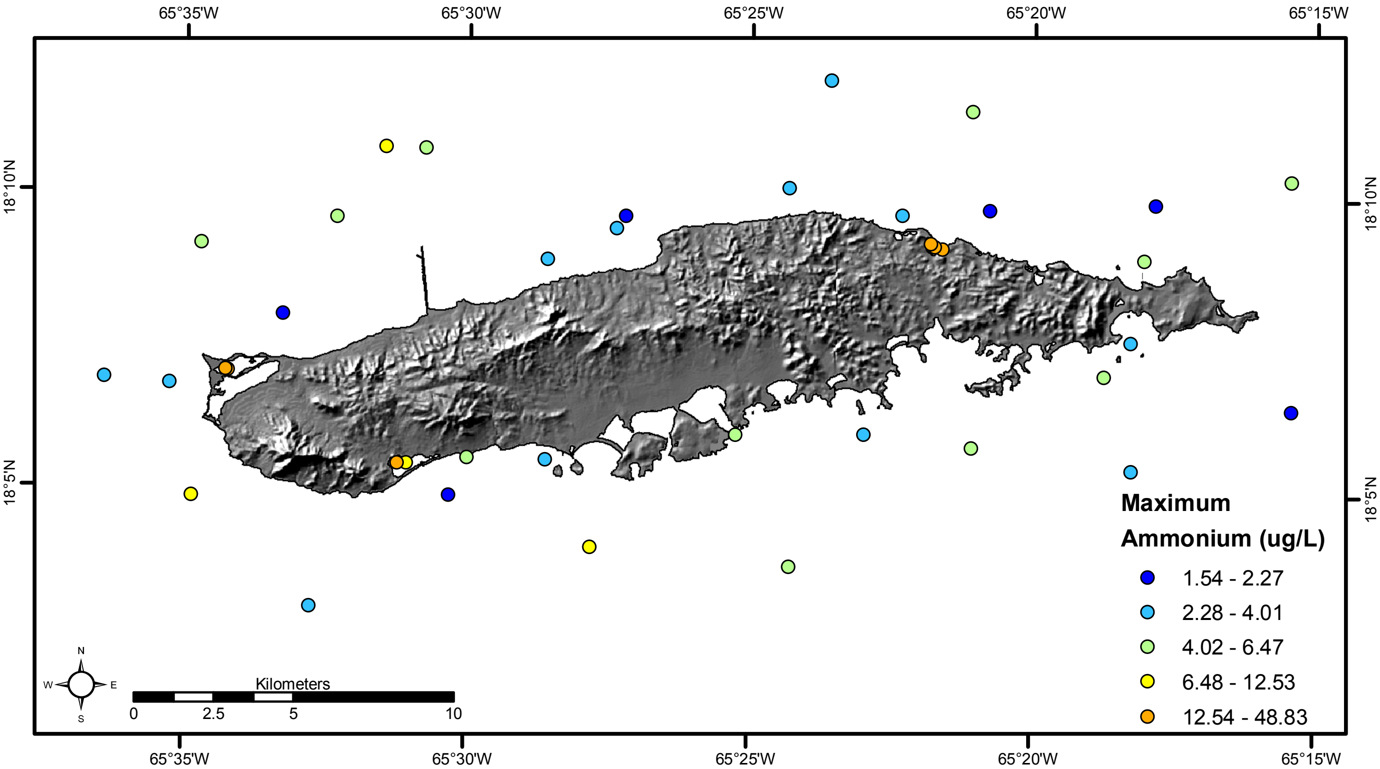


Figure 6.6. Maximum observed ammonium concentrations (ug/L).

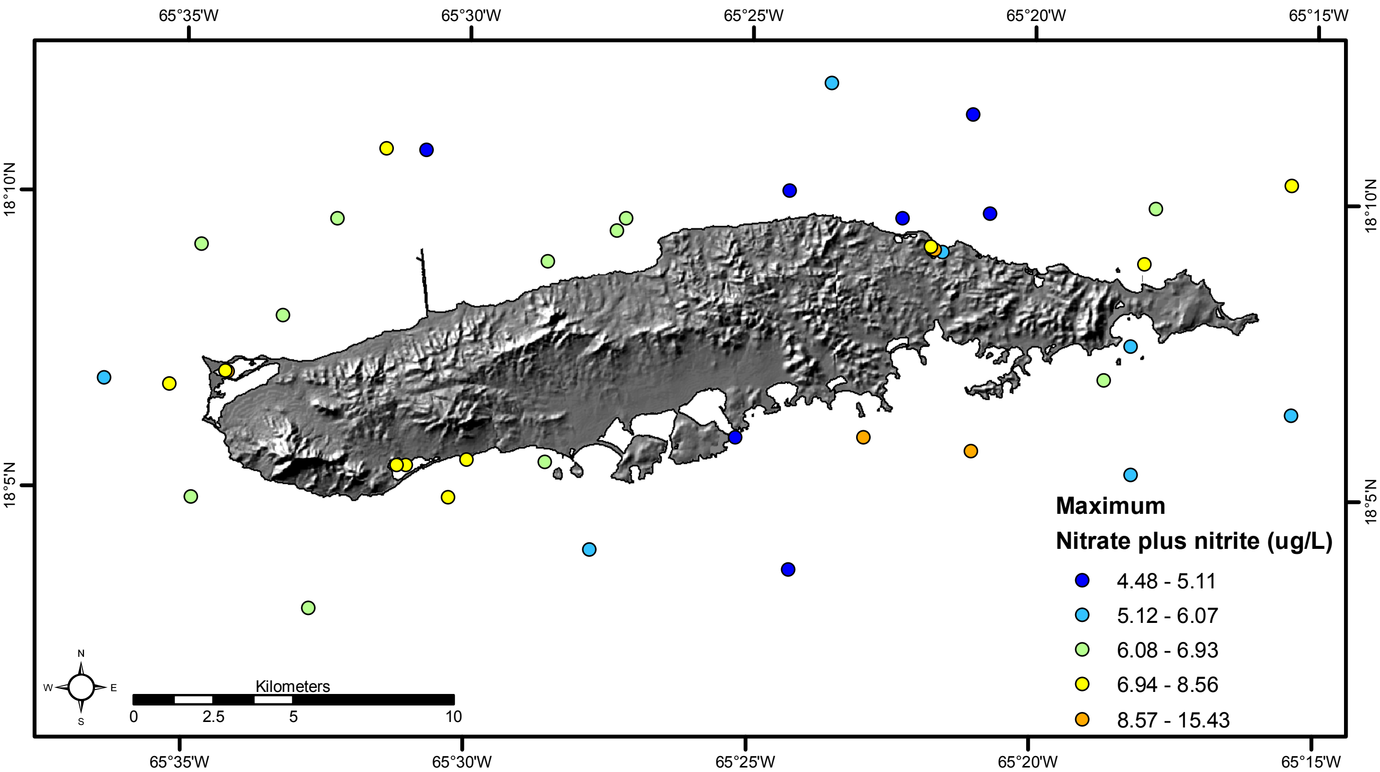


Figure 6.7. Maximum observed nitrate plus nitrite concentrations (ug/L).

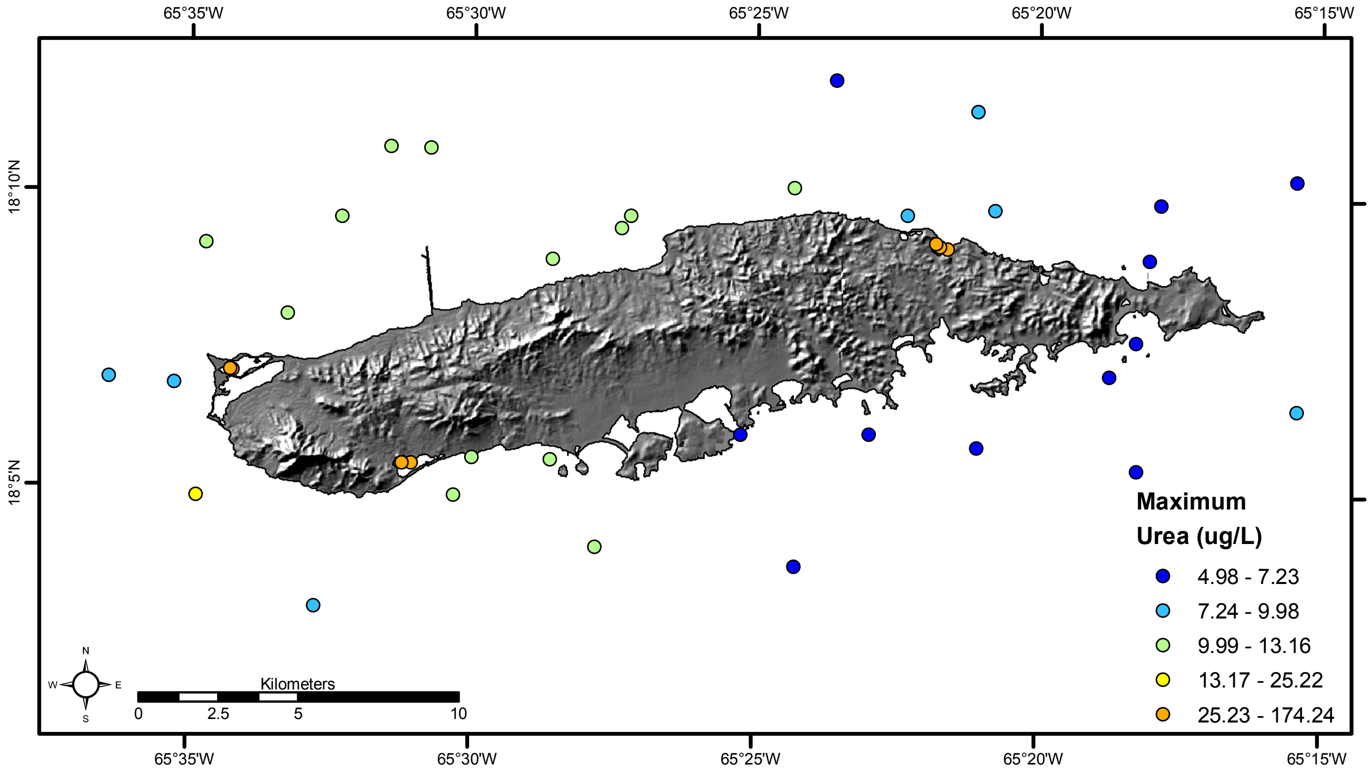


Figure 6.8. Maximum observed urea concentrations (ug/L).

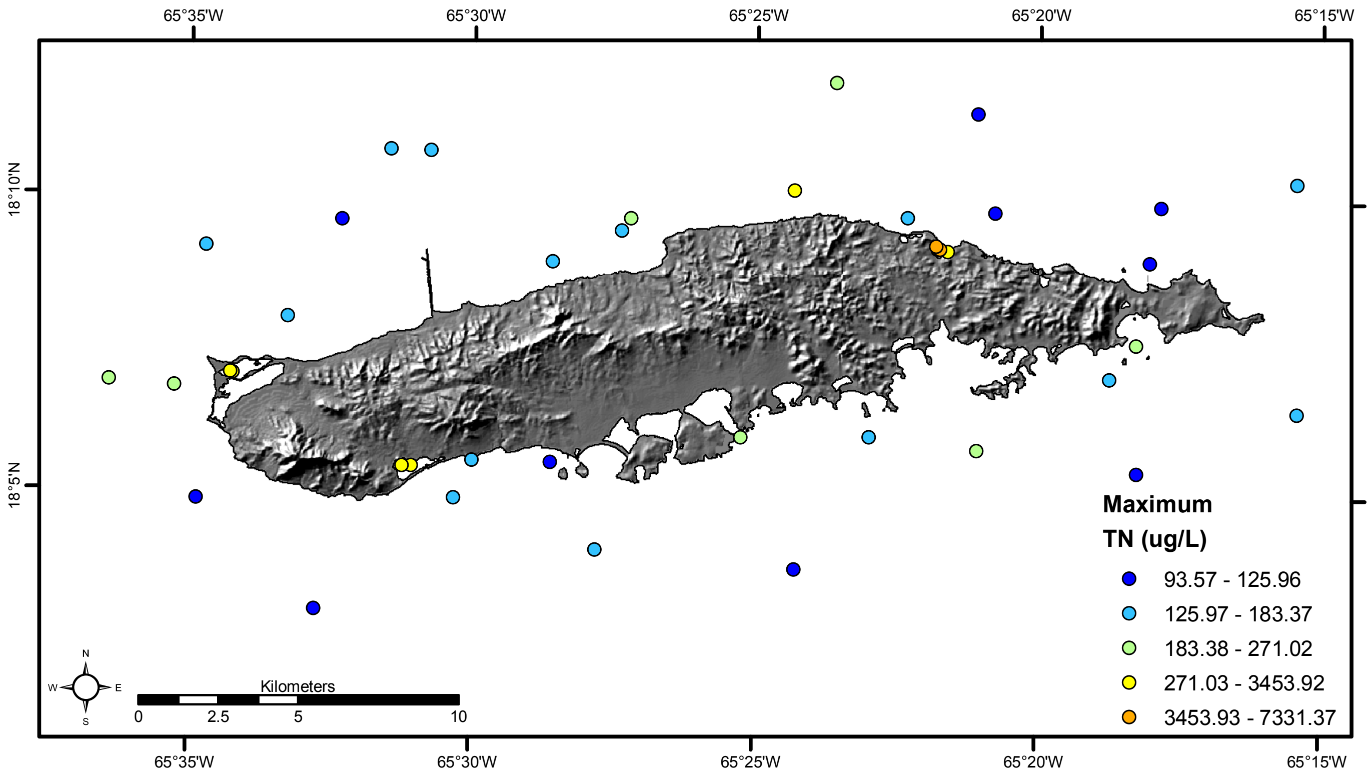


Figure 6.9. Maximum observed total nitrogen (TN) concentrations (ug/L).

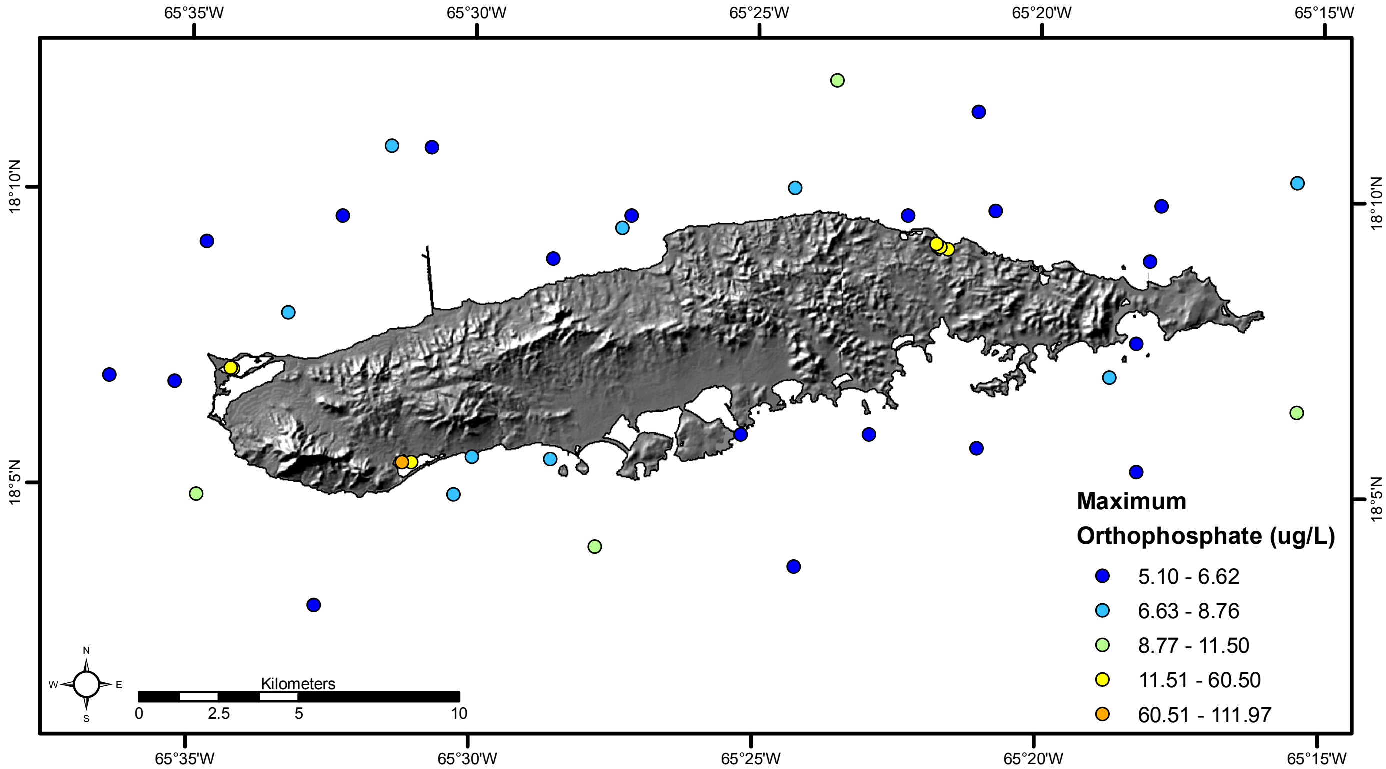


Figure 6.10. Maximum observed orthophosphate concentrations (ug/L).

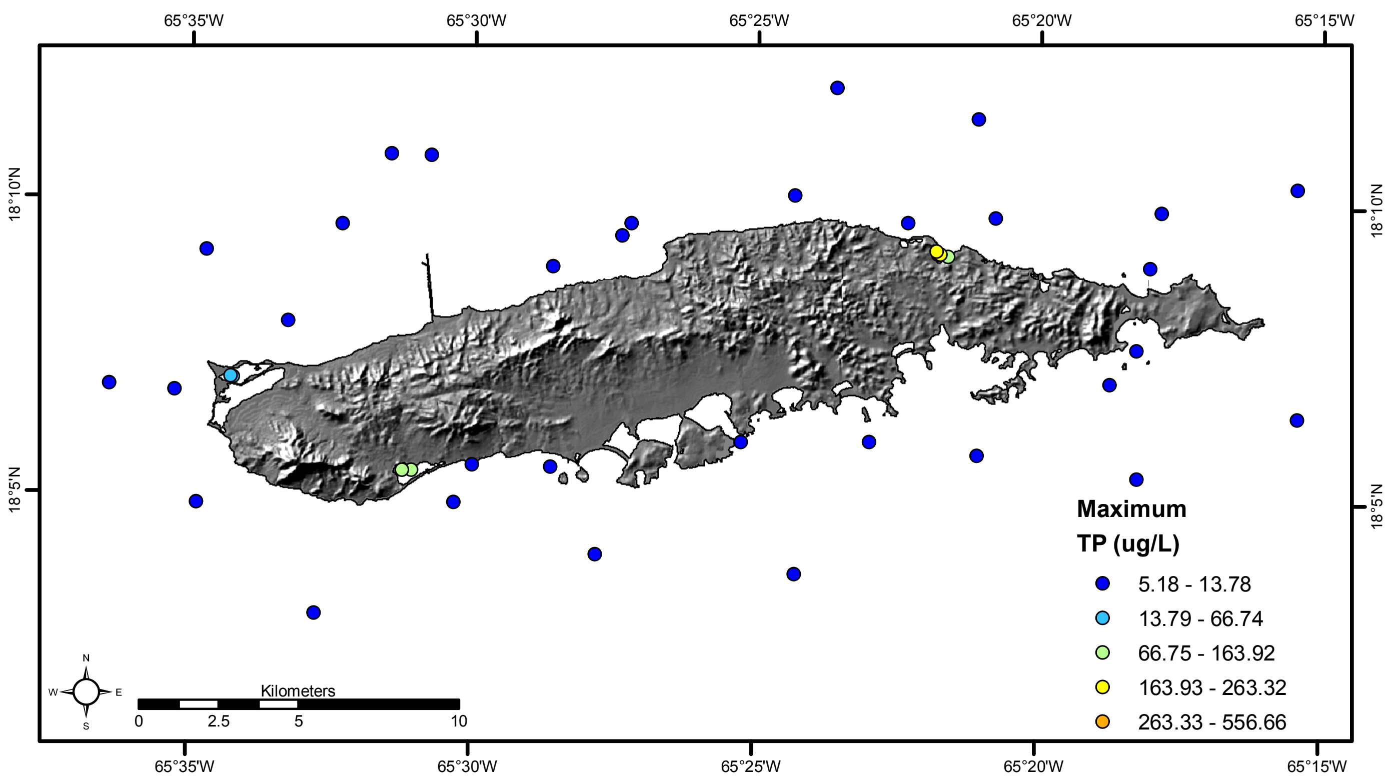


Figure 6.11. Maximum observed total phosphorus (TP) concentrations (ug/L).

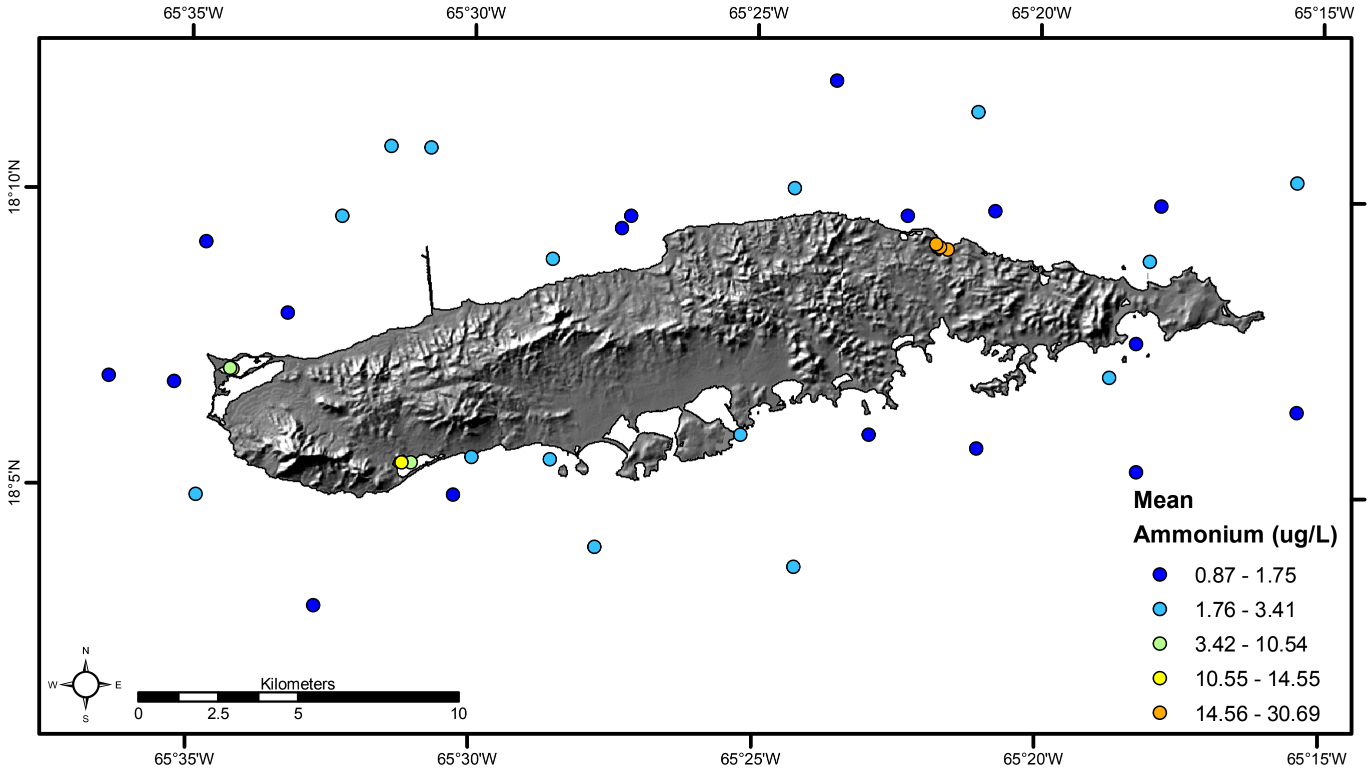


Figure 6.12. Mean observed ammonium concentrations (ug/L).

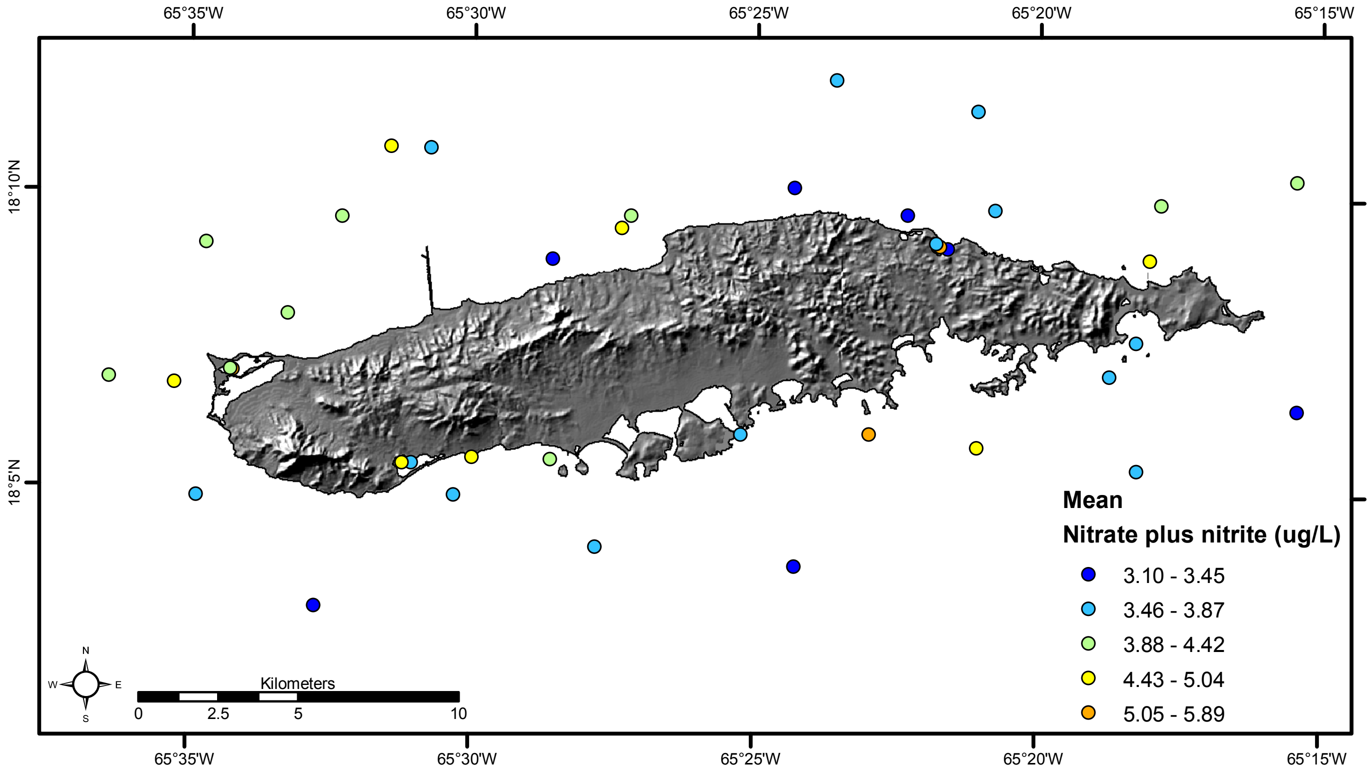


Figure 6.13. Mean observed nitrate plus nitrite concentrations (ug/L).

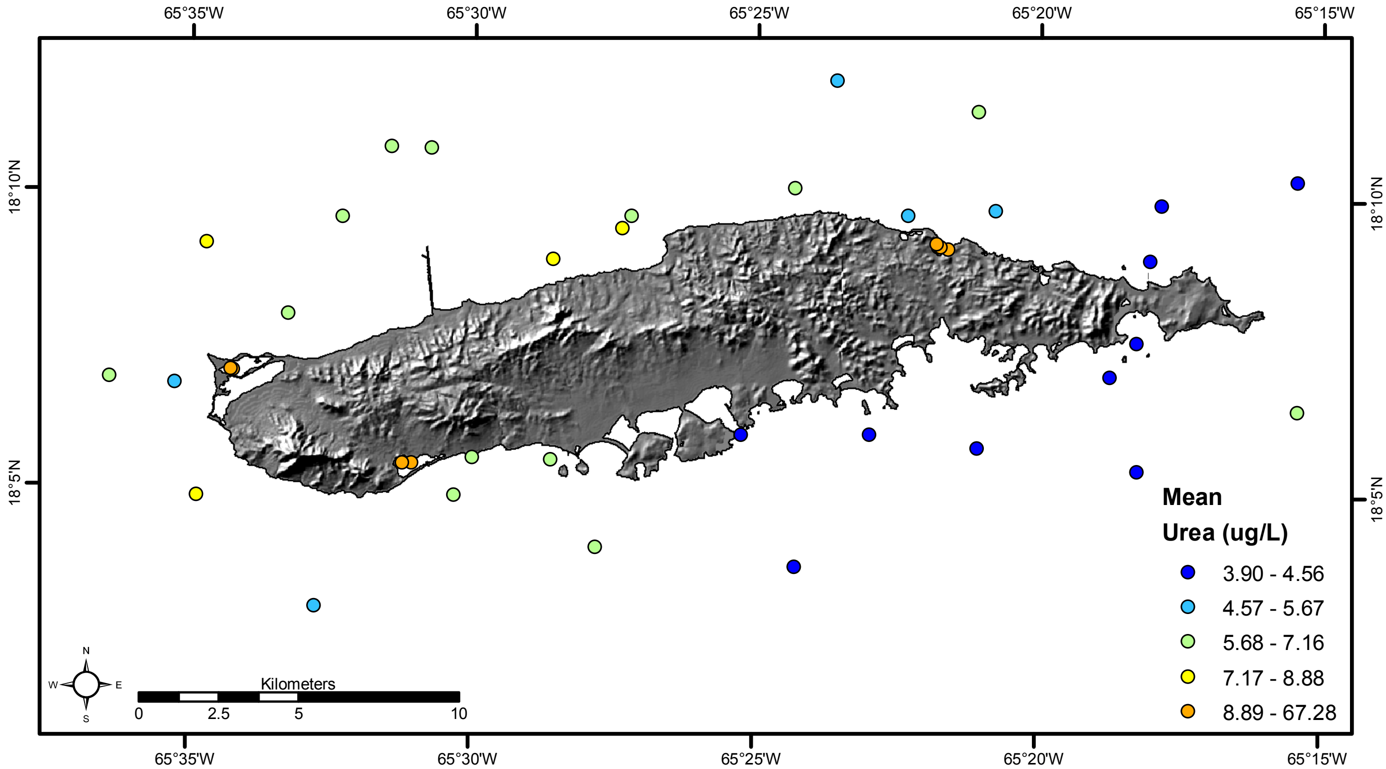


Figure 6.14. Mean observed urea concentrations (ug/L).

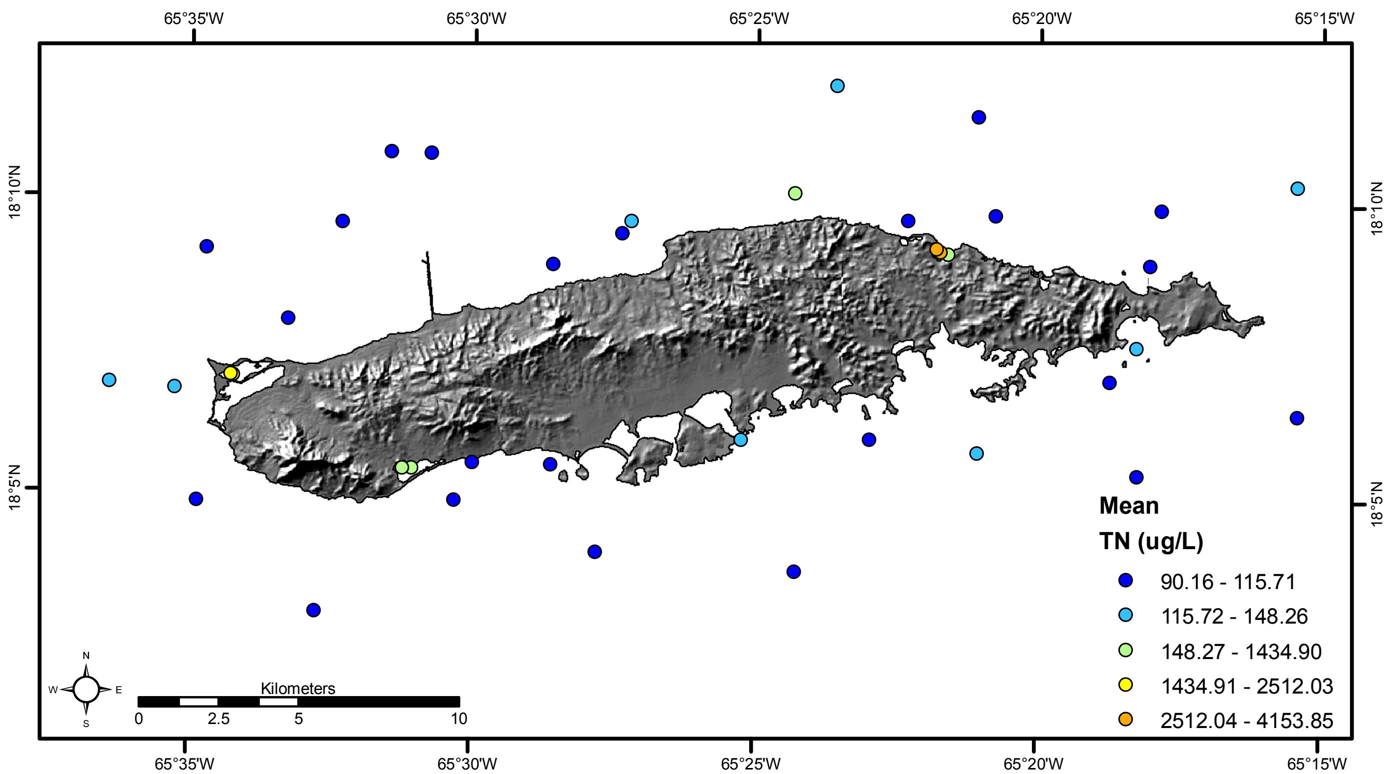


Figure 6.15. Mean observed total nitrogen (TN) concentrations (ug/L).

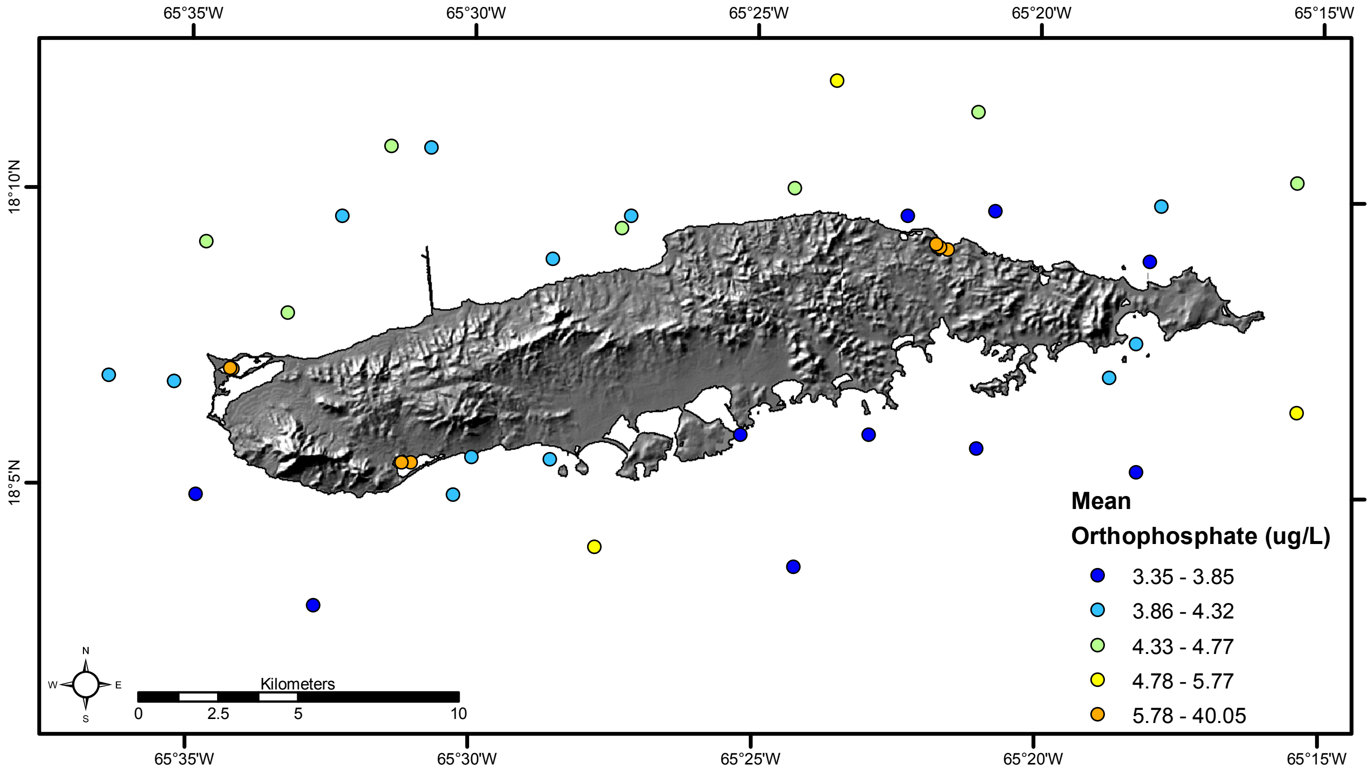


Figure 6.16. Mean observed orthophosphate concentrations (ug/L).

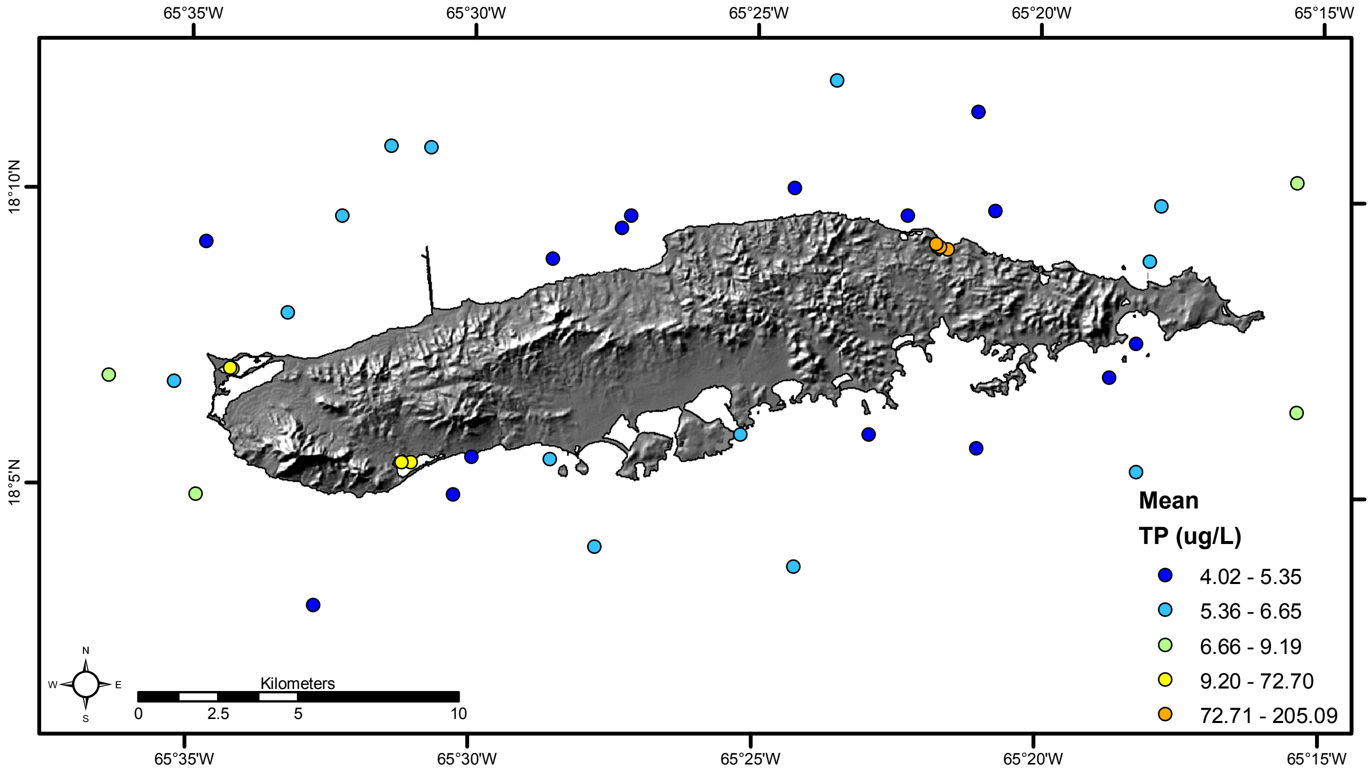


Figure 6.17. Mean observed total phosphorus (TP) concentrations (ug/L).

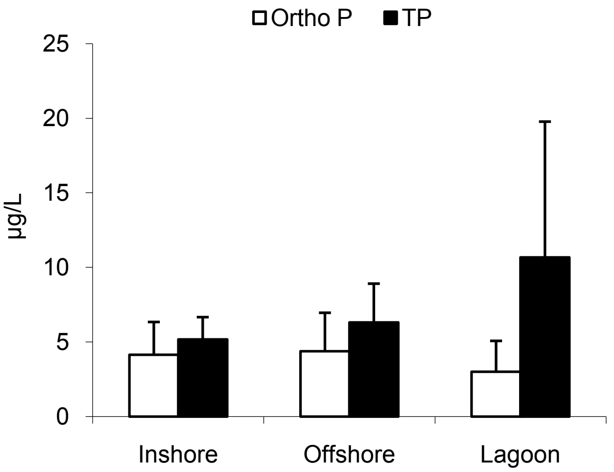


Figure 6.18. Mean concentrations of total phosphorus (TP) and orthophosphate by strata. Error bars are one standard deviation. Offshore TP is statistically higher (α=0.05) than inshore TP (no significant differences among other groups).

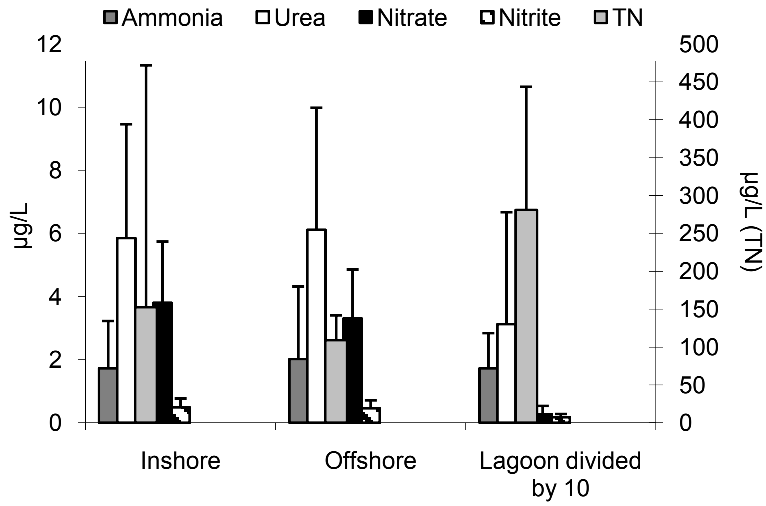


Figure 6.19. Mean concentration of nitrogen by strata. Error bars are one standard deviation. For all analytes, lagoon concentrations are statistically higher (α=0.05) than inshore and offshore.

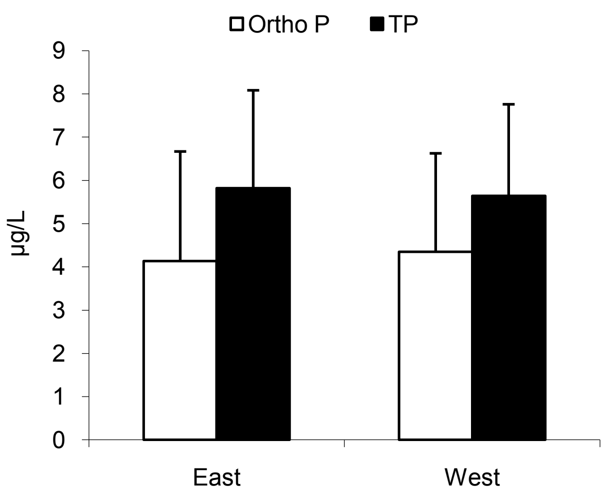


Figure 6.20. Mean concentrations of total phosphorus (TP) and orthophosphate for east versus west. Error bars are one standard deviation. No significant differences between east and west.

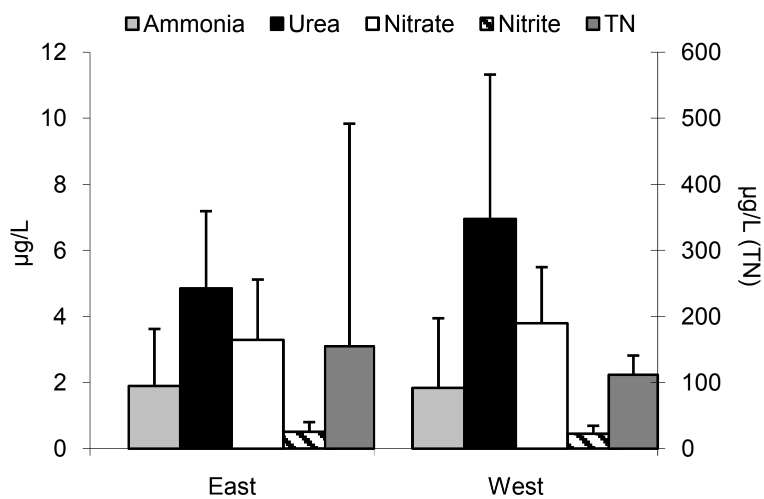


Figure 6.21. Mean concentration of nitrogen for east vs. west for marine (non-lagoon) sites. Error bars are one standard deviation. Urea concentrations on the western part of the island are statistically higher (α=0.05) than on the eastern part of the island. No significant differences for other analytes.

Temporal Patterns

Because there were only two sampling dates during the dry season, and boat/weather problems prevented complete sampling during these dates, it is not statistically valid to compare wet versus dry seasons. Periods of heavy precipitation do not seem to predict nutrient concentrations in lagoon, or inshore and offshore waters (Figures 6.22-6.27, nitrate plus nitrite and orthophosphate data shown). There are sampling points (e.g., August 30, 2007) when very heavy rainfall in the 5 day period before sampling caused elevated concentrations of nitrate plus nitrite, but not concentrations of orthophosphate. This is unexpected because phosphorus is tightly tied to soil particles, so as runoff increases, phosphorus transport would be expected to increase. Conversely, there are sampling points (e.g., January 31st, 2008) when concentrations are elevated but the preceding 5 days were relatively dry. The apparent disconnect between precipitation (and therefore runoff) has several possible explanations. First, it is possible that watershed nutrient inputs are not important to the nutrient budgets of the system. Second, it is possible that biological processes (uptake, denitrification) dampen the runoff signal in coastal waters. Finally, because nutrients can change on the time scale of hours, it is possible that there are shorter term fluctuations in nutrient concentrations that were not captured in this study. Similarly, there could be long term patterns in nutrient concentrations that were not captured during this one year dataset. These research questions could be answered with further study and monitoring.

Comparison with Critical Thresholds

From a regulatory perspective, no nutrient criteria exist for U.S. coastal waters. However, for coral reef ecosystems, it has been suggested that 14 µg-N/L dissolved inorganic nitrogen (DIN) and 31 µg-P/L soluble reactive phosphorus (SRP) are the threshold values above which macroalgal growth can threaten coral reefs (Lapointe, 1997). In Vieques, the inshore and offshore waters never exceeded 14 µg/L of DIN (nitrate + nitrite + ammonium). Although there is no proposed threshold for total nitrogen (TN), TN concentrations in the coastal waters of Vieques did exceed the level for DIN. It should be noted that DIN is much more readily available for plant or phytoplankton uptake than TN, so high TN is not necessarily indicative of an ecological problem. The suggested threshold value for phosphorus (31 µg-P/L) was exceeded only in the lagoons, suggesting that P is not a problem in nearshore or offshore waters.

Comparison with Other Sites in Puerto Rico

Nutrient concentrations observed in Vieques can be compared to observations in other locations in Puerto Rico (Figure 6.28). Coastal (non-lagoon) nutrient concentrations presented here for Vieques are higher than data reported in southwest Puerto Rico (comparing TN and TP; Pait et al. 2007). It should be noted that the southwest Puerto Rico data set was based on a one time sampling in August, so it is possible that this is not representative due to temporal nutrient variability. However, data from a monthly long term dataset for Jobos Bay, Puerto Rico (JBNERR 2009) for orthophosphate, ammonium, nitrate and nitrite, concentrations were very similar to lagoon data for Vieques. Jobos Bay is con-

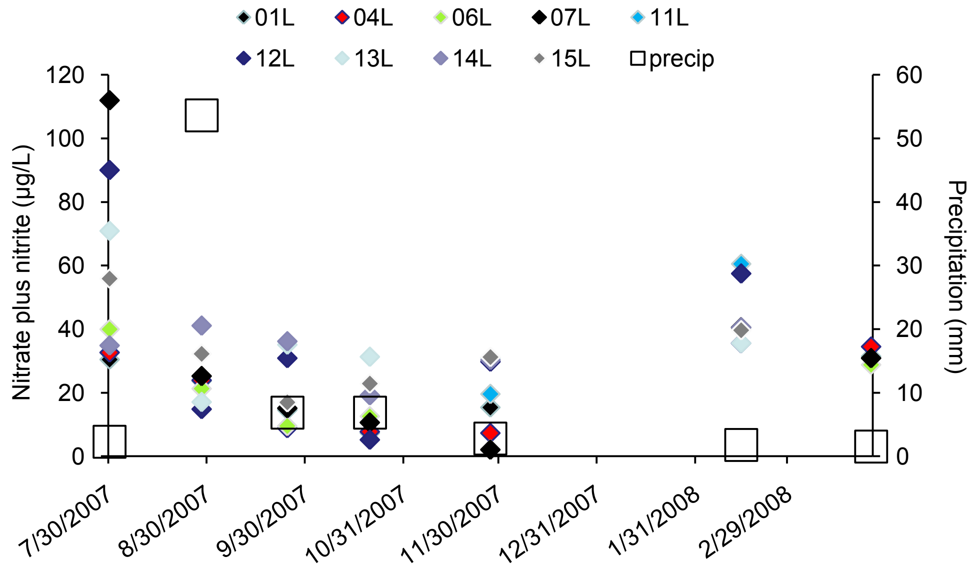


Figure 6.22. Temporal variation in nitrate plus nitrite concentrations in lagoons. Precipitation values show the rainfall in the 5 days preceding sampling.

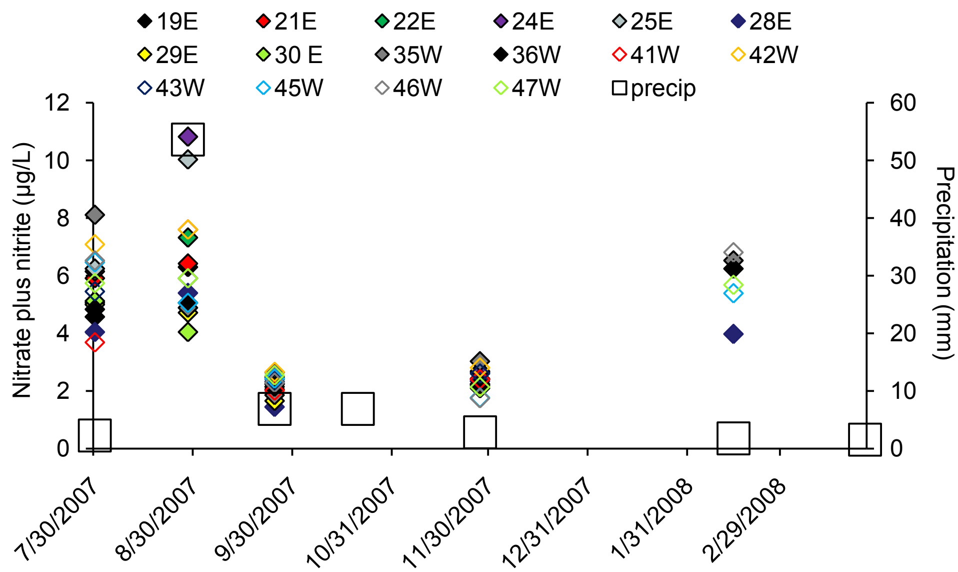


Figure 6.23. Temporal variation in nitrate plus nitrite concentrations inshore. Precipitation values show the rainfall in the 5 days preceding sampling.

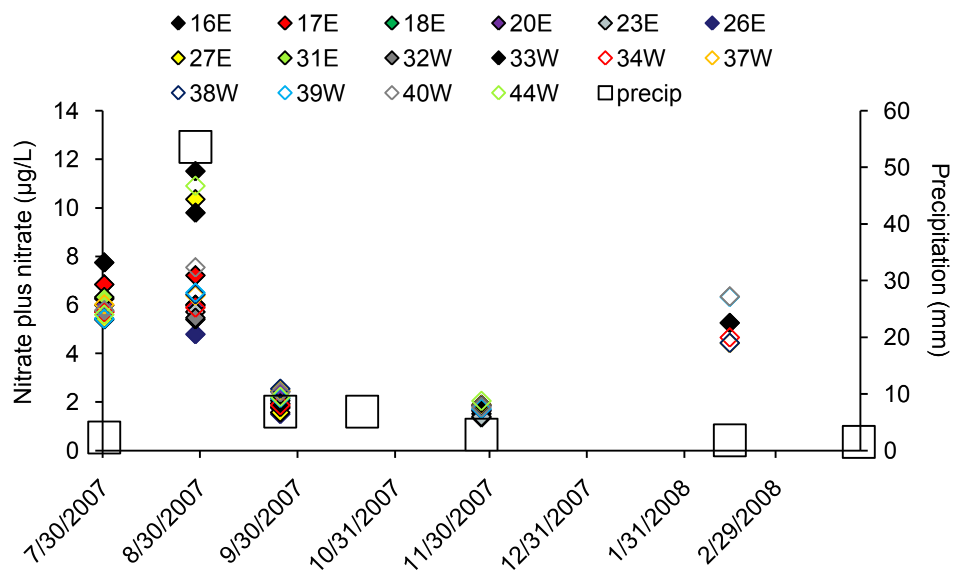


Figure 6.24. Temporal variation in nitrate plus nitrite concentrations offshore. Precipitation values show the rainfall in the 5 days preceding sampling.

sidered to be impacted by both point and non-point source nutrient pollution (Bowen and Valiela 2008). Despite having similar nutrient levels, Jobos Bay is hydrographically and ecologically dissimilar from the lagoons on Vieques, in that Jobos Bay is much larger, much deeper (maximum depth=10m, Jobos Bay Estuarine Profile 2002), better flushed and has less organic matter than the lagoons. It is hypothesized that the high nutrient levels in the Vieques lagoons are the natural state and do not represent anthropogenic enhancement.

Detecting Changes in Sea Surface Chlorophyll and Turbidity Using Remote Sensing

Nutrient concentrations can affect both benthic macroalgae as well as phytoplankton in the photic zone. Understanding of the temporal variability and annual cycles can be helpful in identifying hot spots. In marine and coastal ecosystems, an understanding of the expected sea surface annual cycle can be used to: (1) identify dominant forcing agents and processes; (2) isolate trends and impacts of anomalous events from seasonal cycles; and (3) plan sampling strategies to resolve important cycles. This can be applied to both chlorophyll, as well as turbidity. Turbidity can be used a proxy for sedimentation rates which can have adverse effects on corals.

Currently, there is little *in situ* data to define the annual cycle of sea surface chlorophyll, chlorophyll variability, and water clarity around Vieques. In this study, we utilized the recent advances made in the fields of marine optics and remote sensing to determine fundamental but currently unknown information about the local water quality: namely, the annual cycle of surface chlorophyll and backscattering (a surrogate for turbidity)

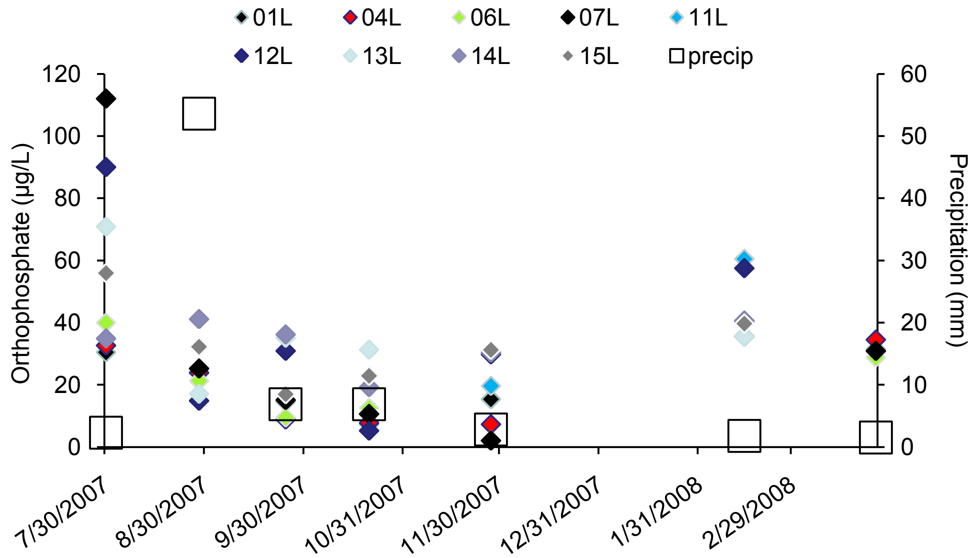


Figure 6.25. Temporal variation in orthophosphate concentrations in lagoons. Precipitation values show the rainfall in the 5 days preceding sampling.

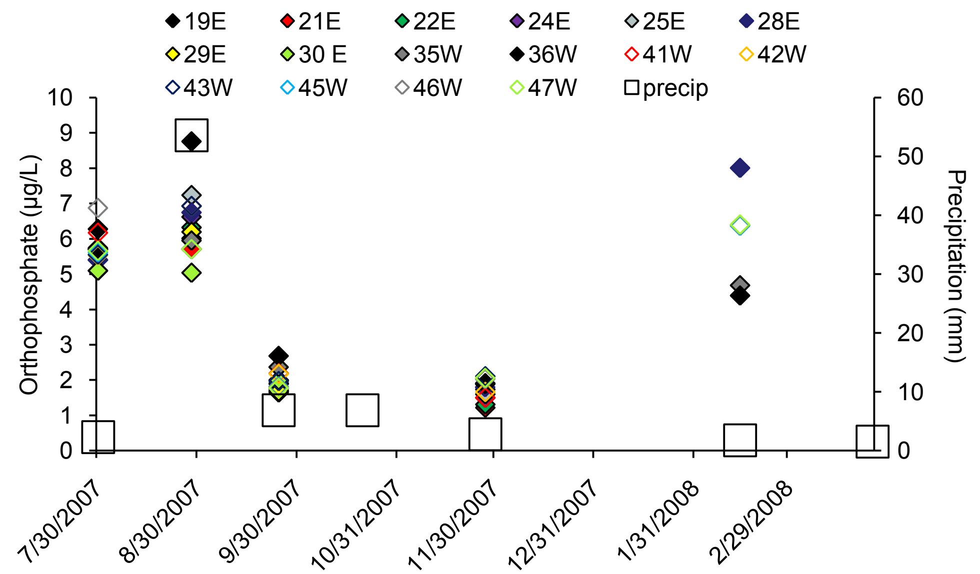


Figure 6.26. Temporal variation in orthophosphate concentrations inshore. Precipitation values show the rainfall in the 5 days preceding sampling.

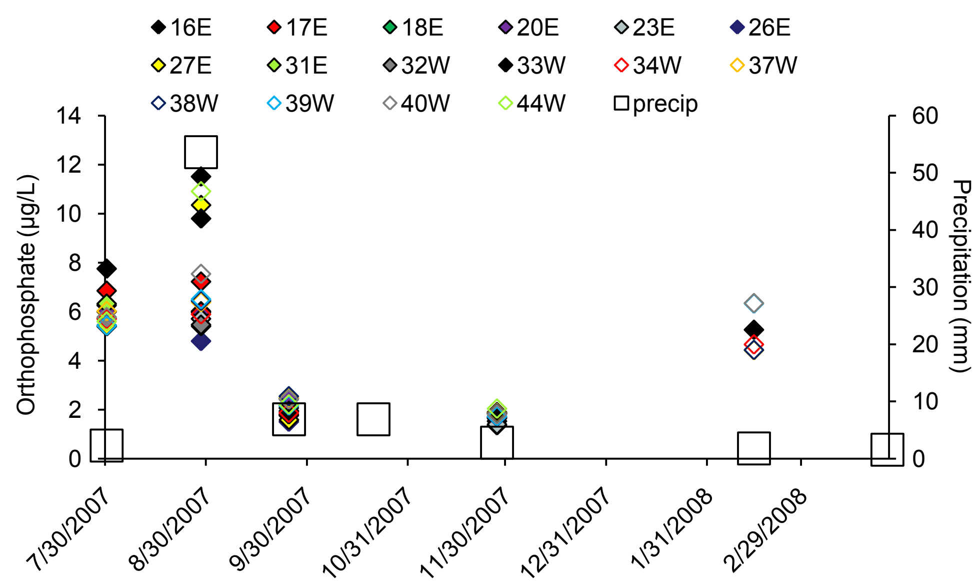


Figure 6.27. Temporal variation in orthophosphate concentrations offshore. Precipitation values show the rainfall in the 5 days preceding sampling.

along the northern and southern coasts of Vieques. Surface chlorophyll and backscattering information were obtained from SeaWiFS (Sea-viewing Wide Field-of- view Sensor) images from 1998 through 2007. We focused on two transects: northern coast (labeled as N to N', Figure 6.29) and southern coast (labeled as S to S', Figure 6.29). They are shown in white in Figure 6.29. Under each map is a Hovmoller diagram (a graph that simultaneously captures temporal and longitudinal variability) that shares the same longitude axis. Each location along the transect consists of 365 expected values, one for each day. An expected value is defined as the median of the data at the same location and Julian day regardless of the year. The cycle shows:

1) Along the northern coast, a chlorophyll front sits near the middle of the island throughout the year (Figure 6.29a). Chlorophyll west of the front is ~ 1 µg/L; that east of the front is ~0.3 µg/L.

2) Along the southern coast, lowest chlorophyll occurs in the summer (Figure 6.29b). In the fall and winter, chlorophyll in the middle of the island is slightly elevated (green, ~ 0.5 µg/L) compared to the tips of the island (~0.15).

3) Along the northern coast, a turbidity front sits slightly off center in the winter (Figure 6.29c). Water is more turbid west of this front.

4) Along the northern coast, annual maximum turbidity usually occurs on the west side of the island in December (Figure 6.29c).

5) Along the southern coast, water is relatively clear throughout the year (Figure 6.29d).

The *in situ* data collected as part of this study are not sufficient to characterize the drivers behind these observed patterns in chlorophyll and turbidity. Further *in situ* studies are required to better understand the driving forces behind these observed patterns in chlorophyll and turbidity, including the relative roles of physical oceanographic forcing factors, storm events and land based sources of pollution.

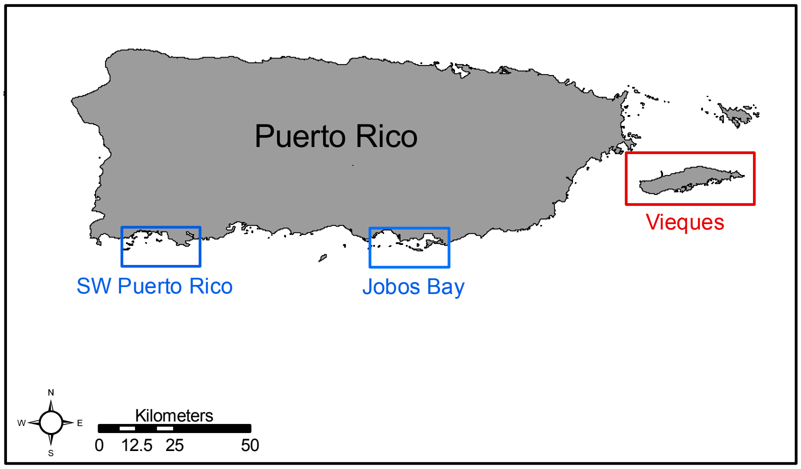


Figure 6.28. Location of other nutrient study sites in Puerto Rico.

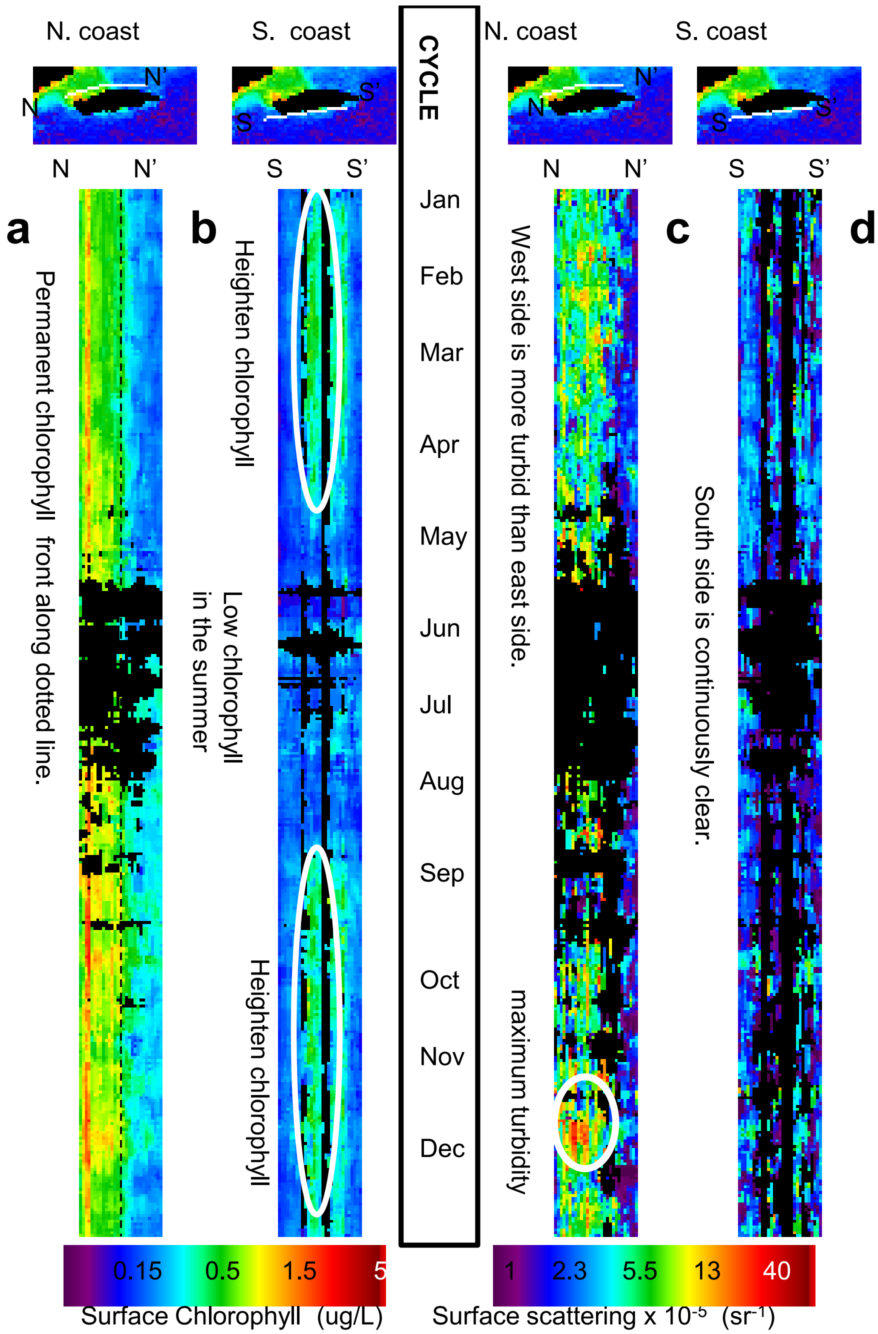


Figure 6.29. Remotely sensed (SeaWIFS) chlorophyll and turbidity patterns.

6.4 SUMMARY AND CONCLUSIONS

Nutrient concentrations in the coastal waters of Vieques are similar in magnitude to what has been observed elsewhere in Puerto Rico. The highest concentrations were found in the lagoons. We hypothesize that this is the natural state of these lagoons, rather than an indication of nutrient pollution hot spots because the lagoons are shallow, poorly flushed and high in organic matter. These data do not suggest that there is currently a problem with anthropogenic nutrient over enrichment in Vieques. However, these data will serve as critical baseline information that will allow coastal managers to take proper steps to insure that development pressure on the island do not increase the nutrient flux to coastal waters, thereby increasing stressors to coral reef ecosystems.

ACKNOWLEDGMENTS

Funding for this work was provided by NOAA's Office of Response and Restoration. The authors would like to thank Kimani Kimbrough, Timothy Wynne, Robert Warner and Clifford Cosgrove (NOAA) for their assistance with field work. Jason Rolfe and Diane Wehner (NOAA) participated in valuable discussions regarding study design. The logistical challenges of the field operations could not have been overcome without the extensive cooperation of Oscar Diaz, Sandra Ortiz, Matthew Connolly (USFWS), Mark Martin (Vieques Conservation and Historical Trust), Dennis Ballam, Ted Dingle, Stacin Martin, and Timothy Garretson (CH2M Hill). Carlton Finley, John Noles, and Christopher Penny (NAVFAC Atlantic) were instrumental in securing access to restricted areas for the research team. Captain Franco Gonzalez (Caribbean Flyfishing Company) and Captain Angel Nazario (*Aquanauta*) provided excellent vessels for the field work.

LITERATURE CITED

Armstrong, F.A.J., C.R. Stearns and J.D.H. Strickland. 1967. The measurement of upwelling and subsequent biological processes by means of the Technicon Autoanalyzer and associated equipment. Deep Sea Research 14(3): 381-389.

Bernhardt, H. and A. Wilhelms. 1967. The continuous determination of low level iron, soluble phosphate and total phosphate with the AutoAnalyzer. Technicon Symposium.

Bowen, J.L and I. Valiela. 2008. Using d15N to assess coupling between watersheds and estuaries in temperate and tropical regions. Journal of Coastal Research 24: 804–813.

Bricker, S., B. Longstaff, W. Dennison, A. Jones, K. Boicourt, C. Wicks and J. Woerner. 2007. Effects of Nutrient Enrichment in the Nation's Estuaries: A Decade of Change, National Estuarine Eutrophication Assessment Update. NOAA Coastal Ocean Program Decision Analysis Series No. 26. National Centers for Coastal Ocean Science, Silver Spring, MD. 322 pp.

Desert Research Institute. 2009. RAWS USA Climate Archive. http://www.raws.dri.edu/cgi-bin/rawMAIN.pl?txPVIE.

Galloway J.N., J.D. Aber, J.W. Erisman, S.P. Seitzinger, R.H. Howarth, E.B. Cowling and B.J. Cosby. 2003. The nitrogen cascade. BioScience 53: 341-356.

Hansen, H.P. and F. Koroleff. 1999. Determination of Nutrients. In: K. Grasshoff, K. Kremling and M. Ernhardt (Eds). Methods of Seawater Analysis. New York, Wiley-VCH. pp. 159-251.

Harrison, P.L. and S. Ward. 2001. Elevated levels of nitrogen and phosphorus reduce fertilisation success of gametes from scleractinian reef corals. Marine Biology 139: 1057-1068.

Harwood, J.E. and A.L. Kuhn. 1970. A colorimetric method for ammonia in natural waters. Water Research 4: 805-811.

JBNERR. 2009. System Wide Monitoring Program Data for Jobos Bay NERR. http://gcmd.nasa.gov/records/GCMD_CDMO_jobmet01-12.04m.html.

Lapointe, B. 1997. Nutrient thresholds for bottom up control of macroalgal blooms in Jamaica and southeast Florida. Limnology and Oceanography 42: 1119-1131.

Mathews, L.G, F.R. Homans and K.W. Easter. 2002. Estimating the benefits of phosphorus pollution reductions: An application in the Minnesota River. Journal of the American Water Resources Association 38: 1217-1223.

Marubini, F. and P.S. Davies. 1996. Nitrate increases zooxanthellae population density and reduces skeletogenesis in corals. Marine Biology 127: 319-328.

Navarro, A. 2002. Testing water quality in Puerto Rico's beaches: A volunteer experience. Available at: http://acwi.gov/monitoring/conference/2002/Papers-Alphabetical%20by%20First%20Name/Ana%20Navarro-poster.pdf

NOAA. 2007. Vieques Island, Puerto Rico: Database and Mapping Project. NOAA's Office of Response and Restoration. Available at: http://mapping2.orr.noaa.gov/portal/vieques/sitecont_table.html

Pait, A.S., D.R. Whitall, C.F.G. Jeffrey, C. Caldow, A.L. Mason, J.D. Christensen, Mark E. Monaco and J. Ramirez. 2007. An assessment of chemical contaminants in the marine sediments of Southwest Puerto Rico. NOS NCCOS 52. Silver Spring, MD. NOAA/NOS/Center for Coastal Monitoring and Assessment. 116 pp.

CHAPTER 7: CONCLUSIONS

Matthew S. Kendall[1], Laurie J. Bauer[1,3], Anthony S. Pait[1], David R. Whitall[1], John S. Burke[2], and Andrew L. Mason[1]*

[1]Center for Coastal Monitoring and Assessment, National Centers for Coastal Ocean Science, National Ocean Service, NOAA, 1305 East-West Hwy, Silver Spring, MD 20910

[2]Center for Coastal Fisheries and Habitat Research, National Centers for Coastal Ocean Science, National Ocean Service, NOAA, 101 Pivers Island Road, Beaufort, NC 28516

[3]Consolidated Safety Services, Inc., Fairfax, VA 22030, under NOAA Contract No. DG133C07NC0616

[*]Corresponding author: matt.kendall@noaa.gov

This report is comprised of a suite of studies investigating fish fauna, benthic communities, nutrient levels, and chemical contaminants in the marine environment adjacent to the former land-use zones around Vieques. The main finding was that overall, there was little difference in marine resources, nutrients, or chemical contaminants around Vieques offshore of the various former land-use zones. This finding was somewhat surprising given the conflicting hypotheses that, 1) U.S. Naval activities could negatively impact adjacent marine ecosystems through mechanisms such as chemical contamination or errant bombing practice, 2) civilian activities could negatively impact adjacent marine ecosystems through mechanisms such as nutrient discharge or overfishing, and 3) much of the land formerly owned by the U.S. Navy was undeveloped and may have been a positive influence on adjacent marine environments by the lack of widespread anthropogenic development activities that are documented to affect coral ecosystems. Although some differences were found in the biota among sampling strata and some elevated contamination and nutrient levels were documented at specific sites around the island, the results of this study do not support any of the hypotheses of land-use history as a major factor structuring the marine environment of Vieques. Nor does it appear to be the case that the marine resources around Vieques are particularly depressed or elevated relative to those of other nearby islands. Instead, the biota, nutrients, and chemical contaminant levels around Vieques generally match those for other coral reef ecosystems in the Puerto Rico and U.S. Virgin Islands region and are likely to have been shaped primarily by regional-scale processes rather than local factors.

By design, components of the studies in this assessment shared many sampling sites, sampling periods, strata, and methods with those used to monitor nearby islands. Results can therefore be easily combined and compared for more integrated analyses. We intentionally did not examine all variables from all studies simultaneously for correlations. Doing so would have yielded a high chance of spurious or random correlations due to the large number of variables involved. Instead, in this chapter we highlight some key observations, point out findings that merit further assessment, and discuss examples where results were integrated across multiple chapters in the report.

The Live Impact Area (LIA) was used for decades as a bombing training range. Why were long term effects of this activity not readily seen in the marine environment during scuba surveys? To better understand this, it is important to recall that the scope of inference for most of this study was the entire marine ecosystem around Vieques. Sampling design was based on randomly placed survey points within several large strata, one of which consisted of waters offshore of the LIA. As such, sampling was not intentionally directed toward specific features such as impact craters (although the random design did result in sediments being sampled from some suspected impact craters). Acute and severe physical impacts from events such as bomb detonation are unquestionable, however, assessment of such specific events was not the objective of the present study. That we found no detectable effects on fish or habitat in scuba surveys, for example, should not be taken as evidence of no impact from

Image 7.1 Unexploded ordnance adjacent to a patch of hardbottom.

bombing activities. Instead it is merely likely that the impacts from bombing were more concentrated in areas closer to shore or nearer the land-based bombing targets and that our randomly placed surveys simply did not encounter them. Other research has directly sought impact craters to quantify such damage (Rogers et al. 1978; DON 1980; Macintyre et al. 1983; DON 1986; Porter 2000; Barton and Porter 2004). Additional sampling could ultimately detect such effects and strata could be added to force sampling into suspected areas. As more time passes since Naval activities ceased in 2003, coral and other benthic cover will continue to regrow, hurricanes will continue to rearrange and create more rubble, and bombing effects will further blend into the natural condition of Vieques' other reefs.

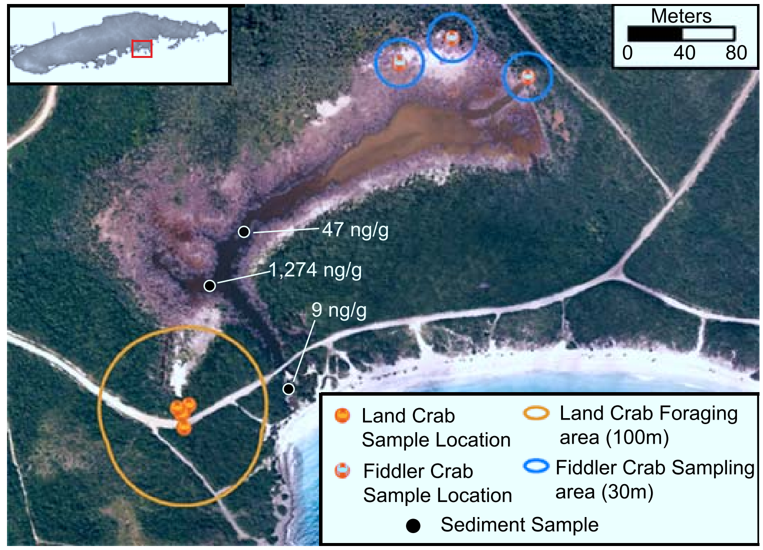


Figure 7.1. DDT levels in sediment samples collected inshore from Playa la Chiva. Crab sample locations from NOAA and Ridolfi (2006) are also displayed.

As part of this project, 78 sediment samples were analyzed for chemical contaminants, including 15 energetics and energetic-related compounds. The presence of energetics could not be confirmed in any of the sediment samples analyzed. A number of possibilities can be suggested for these findings. As noted, the bombing that occurred on Vieques was focused on land-based and nearshore targets. It is likely that many of the sites sampled for sediments and corals in this study were not in an area where ordnance had detonated. Four sites sampled, however, appeared to be in bomb craters and also yielded no confirmed detections of energetics. The detonation of ordnance containing compounds like RDX, HMX and TNT has been reported to result in only small (parts per thousand to parts per million) amounts of these materials remaining at the site of detonation (Hewitt et al. 2003; Walsh et al. 2005). This is in contrast to the higher reported concentrations of energetics found adjacent to at least one unexploded piece of ordnance in Vieques (Barton and Porter 2004). Finally, it is also likely that environmental degradation of any energetics present, even in what appeared to be bomb craters, has occurred since 2003. It is important to note that this study was focused on the sediments and corals of the marine and wetland environments of Vieques. A number of other studies including ATSDR (2003) and CH2M HILL (2002) have assessed the presence of energetics (and other contaminants) in both the terrestrial environment and selected biota (fish, ATSDR 2003; land crabs, NOAA and Ridolfi 2006). Additional sampling using both targeted and randomized strategies to examine particular features (e.g., only four bomb craters were sampled in the present study), key habitats, biota, and the ecological connections among them is warranted to further characterize the presence of energetics around Vieques.

While chemical contaminants were generally below known levels of concern, there were a few exceptions. The most noteworthy being the very high level of DDT observed in the inland lagoon north of Playa la Chiva (Blue Beach). The high levels of parent compound (DDT) and relatively low proportion of degradation products (DDE) found in sediments may indicate that an old spill or application of DDT persists in the area due to environmental conditions that are not conducive to degradation. Of greater concern, it is also possible that given the extremely high parent compound values, there may be a source of non-degraded DDT still leaking from a container. Both the overall extent and the maximum concentration of contamination in this area are unknown. Only three samples were taken in this salt pond and these were within 250 meters of each other (Figure 7.1). Only the central sample had the highly elevated DDT levels. Additional sampling in and around this area is needed to determine the extent and concentration of contaminated soils and possibly identify the source of the contaminant. While separated from the marine waters off Playa la Chiva at the time of sampling by a low sand berm, this salt pond presumably has a periodic connection with and is flushed into the reef ecosystem to the south. It is important to note that the high DDT concentrations seen here were measured in sediments. Land crabs and fiddler crabs were sampled from nearby forests in 2005 (NOAA and Ridolfi 2006) although the suspected foraging range of the specific crab samples did not overlap with the sediment sample with high DDT. While DDT/DDE was detected in crab tissues, concentrations were below levels known to cause adverse health effects in children and adults (ATSDR 2006). Biota such as consumable fish and crabs should be sampled more thoroughly in the area to identify pathways of trophic transfer and determine the potential for human health effects.

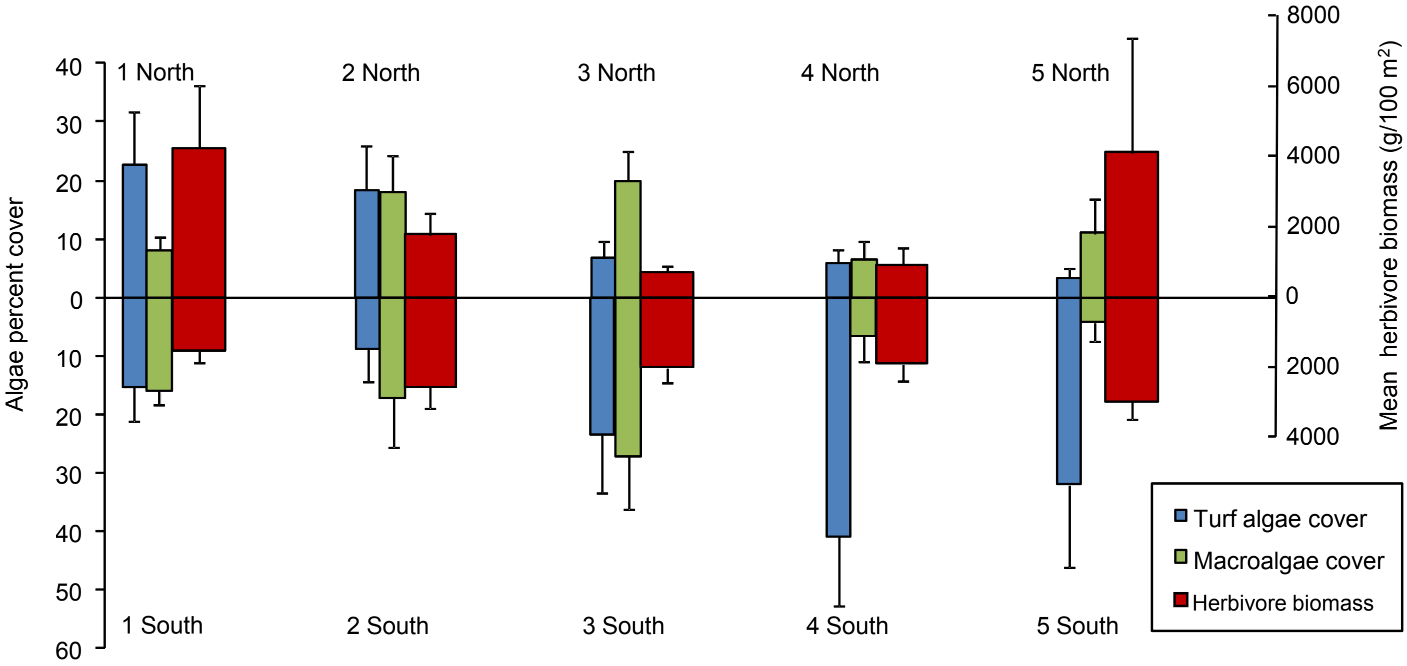


Figure 7.2. Mean (±SE) percent turf and macroalgal cover, and herbivore biomass across strata.

Like most of the Caribbean, algae was the dominant cover type encountered on scuba surveys of Vieques reefs although percent cover varied considerably among strata. Macroalgae had higher cover in the central and western strata (Figure 7.2). This observation was consistent with the hypothesis that anthropogenic sources of nutrients from the civilian area may have caused the higher algal concentrations in the central strata and those down current in the strata to the west. Cover of turf algae also differed among strata with highest values in the northwest and southeast strata (Figure 7.2). The nutrient levels observed in this study, however, did not have a pattern consistent with that of algal coverage (turf or macro-algae or both combined) and showed no evidence of an anthropogenic or land based source of pollution. The recent pattern of algal dominance on Caribbean reefs is thought to be due to the combined effects of massive die-offs of the dominant coral species through disease and bleaching, nutrient enrichment, and primarily, the severe depression of algal grazers such as urchins and herbivorous fish through disease and overfishing (Lapointe 1997; Littler and Littler 2007; Sotka and Hay 2009). Biomass of herbivorous fish was indeed inversely related to macroalgal cover on the north shore of Vieques. This observation is consistent with the hypothesis that heavy grazing controls algal cover, however, this same pattern was not evident on the south shore of Vieques. The interesting patterns in algal cover observed among strata around Vieques may be due primarily to factors other than herbivore grazing or nutrient enrichment such as simple habitat differences.

Fish communities of Vieques were similar in composition and biomass to those seen elsewhere in the US Caribbean. One exception was for overall snapper biomass and density on hard bottom, especially along the south shore of Vieques (Figure 3.31). Values there were more than twice as high as on similar habitats in Parguera, Puerto Rico, an area for which comparable data is available (Figure 3.45). The south shore of Vieques has an abundance of juvenile fish habitat for snappers in the form of bays, lagoons, seagrass meadows, and mangroves. It is possible that adult or juvenile habitat, or both, are higher quality around Vieques than Parguera and therefore they support higher snapper densities. This pattern is not consistent among other fish families and community measures (e.g., species richness or diversity) and may be due to random aspects of recruitment success. The causes of different snapper abundance in these two locales are worthy of further investigation.

Recent attention has been given to the potential for establishment of a marine protected area (MPA) in Vieques (Shvilani 2007; H.R. 5864 2008). Further, the findings of the current and other recent studies (e.g., Kendall and Eschelbach 2006) coupled with the recent conversion of large portions of Vieques land into a National Wildlife Refuge represent a potential opportunity for marine conservation. Marine resources are in similar condition to those elsewhere in the region and do not appear especially degraded or impacted by either Naval or civilian use. Much of Vieques' land is now preserved and will be allowed to return to a natural state which will greatly limit many of the negative impacts to coral reef ecosystems that are associated with watershed development. The bioluminescent bay, which was designated the Reserva Natural Bahia Puerto Mosquito as part of the

Puerto Rico Coastal Zone Management Program (PRCZMP) in 1989, is a rare ecological treasure that was targeted for further protection in proposed congressional legislation (H.R. 5864 2008). Additionally, the Compania de Parques Nacionales operates Sun Bay to the east, and currently the Fish and Wildlife Service controls land-based access to the eastern coastal areas. In a recent community study, stakeholder groups expressed a variety of opinions on the establishment of an MPA in Vieques, but many agreed that protection of the marine environment needed to be improved (Shivlani 2007). There are additional attributes that suggest an MPA would be locally beneficial to Vieques and Puerto Rico. Vieques has a full diversity of representative marine habitats in close proximity to each other from mangrove lined bays to shelf edge coral reefs. This density of ecosystem features can be more efficiently encompassed at Vieques relative to conserving target habitats that are more widely spread out elsewhere in Puerto Rico. In addition, the prevailing currents in this region place Vieques upstream relative to the rest of Puerto Rico for much of the year. Although much research remains on the topic, healthy fish and larval production in a Vieques MPA may be exported to and benefit other parts of Puerto Rico more than an MPA positioned farther downstream. Collectively, these features make local coral reef ecosystems, marine zoning, and MPA planning a valuable opportunity for conservation, ecotourism, and fisheries management for Vieques and Puerto Rico.

A wide diversity of additional ecological connections and management alternatives could be investigated by combining the data collected for this report with data from previously existing studies summarized in Part I of this series (Bauer et al. 2008) and other types of information entirely such as socioeconomic surveys (Shivlani 2007). Further investigation of Vieques' marine ecosystems using the data in this series of reports is encouraged. Data for this and our other nearby studies in the region are available at no cost and can be querried and downloaded on the internet. For more information please visit the site:

http://ccma.nos.noaa.gov/ecosystems/coralreef/vieques.html

LITERATURE CITED

ATSDR. 2003a. Petitioned public health assessment, soil pathway evaluation, Isla de Vieques Bombing Range. Agency for Toxic Substances and Disease Registry, Federal Facilities Assessment Branch, Division of Health Assessment and Consultation. Available at: http://www.atsdr.cdc.gov/HAC/PHA/isladevieques/idv_toc.html. Last accessed: 10 December 2008.

ATSDR. 2006. Health Consultation: Land crab evaluation, Isla de Vieques. Agency for Toxic Substances and Disease Registry, Division of Health Assessment and Consultation. Available at: http://www.atsdr.cdc.gov/HAC/pha/IsladeViequesBombingRange/IsladeViequesBombingRange.pdf. Last accessed: 8 March 2010.

Barton, J.V. and J.W. Porter. 2004. Radiological, chemical, and environmental health assessment of the marine resources of the Isla de Vieques Bombing Range, Bahia Salina del Sur, Puerto Rico. Underwater Ordinance Recovery, Inc. and the University of Georgia Institute of Ecology. 44 pp.

Bauer, L.J., C. Menza, K.A. Foley, and M.S. Kendall. 2008. An ecological characterization of the marine resources of Vieques, Puerto Rico. Part I: Historical data synthesis. Prepared by National Centers for Coastal Ocean Science (NCCOS) Biogeography Branch in cooperation with the Office of Response and Restoration. Silver, Spring, MD. NOAA Technical Memorandum NOS NCCOS 86. 121 pp.

DON (U.S. Department of the Navy). 1980. Final environmental impact statement for the continued use of the Atlantic Fleet Weapons Training Facility Inner Range (Vieques). Prepared by TAMS (Tippetts, Abbett, McCarthy, Stratton) and Ecology and Environment, Inc.

DON (U.S. Department of the Navy). 1986. Environmental assessment of continued use of the Atlantic Fleet Weapons Training Facility Inner Range, Vieques, Puerto Rico. Prepared by Ecology and Environment, Inc.

Hewitt, A.D., T.F. Jenkins, T.A. Ranney, J.A. Stark, M.E. Walsh, S. Taylor, M.R. Walsh, D.J. Lambert, N.M. Perron, N.H. Collins and R. Karn. 2003. Estimates for explosives residue from the detonation of army munitions. USACOE Engineer Research and Development Center, ERDC/CRREL TR-03-16. 88 pp.

House Resolution (H.R.) 5864. 2008. To designate Puerto Mosquito Bay National Marine Sanctuary in Puerto Rico, and for other purposes. 110th Congress, 2nd Session. 22 April 2008.

Kendall, M.S. and K.A. Eschelbach. 2006. Spatial analysis of the benthic habitats within the limited-use zones around Vieques, Puerto Rico. Bulletin of Marine Science 79(2): 389-400.

Lapointe, B.E. 1997. Nutrient thresholds for bottom-up control of macroalgal blooms on coral reefs in Jamaica and southeast Florida. Limnology and Oceanography 42(5): 1119-1131.

Littler, M.M. and D.S. Littler. 2007. Assessment of coral reefs using herbivory/nutrient assays and indicator groups of benthic primary producers: a critical synthesis, proposed protocols, and critique of management strategies. Aquatic Conservation: Marine and Freshwater Ecosystems 17:195-215.

Macintyre, I.G., B. Raymond and R. Stuckenrath. 1983. Recent history of a fringing reef, Bahia Salina del Sur, Vieques Island, Puerto Rico. Atoll Research Bulletin 268, Smithsonian Institution, Washington DC.

NOAA and Ridolfi. 2006. Final data report for the Vieques Island Biota Sampling Project, Vieques Island, Puerto Rico. National Oceanic and Atmospheric Administration (NOAA) Office of Response and Restoration and RIDOLFI Inc. Seattle, WA.

Porter, J.W. 2000. The effects of naval bombardment on the coral reefs of Isla Vieques, Puerto Rico. Submitted to King and Spaulding, Atlanta, Georgia. 38 pp.

Rogers, C.S., G. Cintron and C. Goenaga. 1978. The impact of military operations on the coral reefs of Vieques and Culebra. Report to the Department of Natural Resources, San Juan, Puerto Rico.

Shivlani, M. 2007. Community studies to determine the feasibility and expectations of marine protected area (MPA) management in Vieques, Puerto Rico. Unpublished report. 38 pp.

Sotka, E.E. and M.E. Hay. 2009. Effects of herbivores, nutrient enrichment, and their interactions on macroalgal proliferation and coral growth. Coral Reefs 28:555-568.

Walsh, M.R., S. Taylor, M.E. Walsh, S. Bigl, K. Bjella, T. Douglas, A. Gelvin, D. Lambert, N. Perron and S. Saari. 2005. Residues from live fire detonations of 155-mm howitzer rounds. USACOE Engineer Research and Development Center, ERDC/CRREL TR-05-14. 20 pp.

United States Department of Commerce

Gary Locke
Secretary

National Oceanic and Atmospheric Administration

Jane Lubchenco
Under Secretary of Commerce for Oceans and Atmospsheres

National Ocean Service

David Kennedy
Acting Assistant Administrator

An Ecological Characterization of the Marine Resources of Vieques, Puerto Rico

Part II: Field Studies of Habitats, Nutrients, Contaminants, Fish, and Benthic Communities - NOAA Technical Memorandum NOS NCCOS 110